Roads in the rainforests: Legacy of selective logging in Central Africa

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Evaluating the temporal and spatial dynamics of logging road networks

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Abstract

Selective logging prevails in tropical forests around the world, posing urgent questions about how to reconcile timber extraction with biodiversity conservation. Roads are those elements of selective logging that are most costly, most visible and they probably have the most far-reaching environmental impacts. While many studies have outlined road related threats to forest ecosystems, little is known about the persistence of logging roads in the forest landscape. This is especially important in Central Africa, where selective logging is the most important type of land use, both in terms of spatial extent and financial yield. In this thesis I analyze the temporal and spatial dynamics of logging road networks in a part of the Congo Basin and apply these findings to make suggestions for forest management. In five chapters I am approaching the subject from different angles and on different scales:

In the introductory chapter, I compare the content and the orientation of scientific literature on logging roads in tropical forests. In general I identified two strains in the literature, one focusing specifically on road related impacts on forest ecosystems and the other giving technical advice in road planning, building and maintenance in order to improve efficiency and reduce impacts. A third, partially distinct direction of research is oriented on the characterization of the spatial distribution and coverage of forest road networks on larger scale to monitor forest exploitation and related degradation.

The second chapter presents a methodology to identify roads in Central African forests based on remote sensing with LANDSAT images. In a time series approach, I used survival analysis to evaluate the temporal dynamics of secondary logging roads over the last 30 years and showed how road persistence differs depending on environmental variables such as geological substrates.

The third chapter approaches the persistence of logging roads from a field based perspective. I carried out vegetation inventories on a chronosequence of roads abandoned between 1985 and 2015. The results showed that road tracks and edges are suitable habitats for commercial species regeneration with rapid changes in the environmental conditions occurring over time. During 30 years after abandonment about one third of the biomass lost for road building has re-captured in subsequent vegetation development.

The fourth chapter analyses the extent of logging road networks in the overall forest landscape. I used the mathematically well-defined Empty Space Function as a novel way to calculate roadless space. I demonstrated how roadless space in intact forest landscapes (declared in 2000) has diminished in general but in particular in FSC-certified logging concessions. I recommend that forest management should make the preservation of large connected forest areas a top priority by effectively monitoring - and limiting - the occupation of space by roads that are accessible at the same time.

The concluding chapter develops management suggestions to apply the findings. I showed that re-opening logging roads in subsequent harvests is rather the exception than the rule. Evaluating benefits, opportunities, costs and risks, I conclude that re-opening roads should be given a higher priority in forest management. Re-using logging roads can spare forests within the same area by avoiding new forest clearing in the vicinity and at a larger scale by sparing unlogged forests from new logging disturbance by intensifying operations on previously logged forests. As a vision for road management, I suggest to actively manage logging roads as transient elements in the landscape until they are reopened. Permanent access roads should only be built in the periphery of continuous forest blocks.

As a perspective for further research, I discuss the trade-offs between the need of roads for development and the environmental impacts. As an example for this, I present evidence for the first major road corridor crossing the Congo Basin that is already under construction. To limit the impacts on the forest, large-scale conservation corridors have to be established, requiring supra-regional landscape planning.

Keywords

Road ecology, Tropical forest, Selective logging, Forest degradation, Roadless space, Land-sparing vs. land sharing, Regeneration, Spatial analyses, Landscape planning

Résumé

Une fraction importante des forêts tropicales dans le monde est exploitée de manière sélective, générant des questions essentielles sur la manière dont il est possible de réconcilier l'extraction du bois et la conservation de la biodiversité. Les pistes forestieres sont le facteur le plus coûteux, le plus visible et probablement celui qui a les impacts environnementaux les plus graves, de l'exploitation sélective. Plusieurs études ont souligné les effets des pistes forestieres sur les écosystèmes forestiers tropicaux, mais généralement sans traiter l'aspect de leur persistance dans les paysages boisés. Cet aspect est particulièrement important en Afrique Centrale, où l'exploitation sélective est le mode d'utilisation des terres le plus étendu spatialement et générateur d'importants revenus financiers. Dans cette thèse, j'analyse les dynamiques spatiales et temporelles des réseaux de pistes d'exploitation dans une partie de l'Afrique centrale, et je prends les résultats en compte pour formuler des propositions dans le cadre des aménagements forestiers. Je traite ce sujet en cinq chapitres, en adoptant dans chacun d'eux des angles et des échelles différents.

Dans le chapitre introductif, je présente la littérature scientifique qui a traité des pistes d'exploitation dans les forêts tropicales. D'une manière générale, j'ai identifié deux axes de recherche dans la littérature, l'un traitant uniquement de l'impact négatif des routes sur les forêts et l'autre focalisé sur des recommandations plutôt techniques pour une meilleure planification, une meilleure construction et un maintien plus efficace des routes dans le but d'en réduire les impacts. J'ai également identifié un troisième axe, plutôt orienté sur la caractérisation de la distribution spatiale des réseaux routiers sur une échelle plus large et utilisé ça comme indicateur de la dégradation des forêts tropicales.

Dans le deuxième chapitre je présente la méthodologie, basée sur l'utilisation d'images satellitaires LANDSAT, qui m'a permis d'identifier les pistes d'exploitation, primaires et secondaires, en Afrique centrale. En utilisant une série chronologique d'images, j'ai réalisé une analyse de survie pour évaluer la dynamique temporelle des pistes secondaires pendant les 30 dernières années et j'ai montré que la persistance des pistes dépendait en partie de différents facteurs environnementaux, en particulier des substrats géologiques.

Dans le troisième chapitre, j'analyse la persistance des pistes d'exploitation sur le terrain. Pour cela, j'ai réalisé des inventaires de végétation sur des pistes plus ou moins anciennement abandonnées (entre 1985 et 2015, donc depuis 30 ans, jusqu'à cette année). Les résultats montrent que la bande de roulement et le bord des pistes constituent des habitats particulièrement favorables pour la régénération des espèces commerciales, tout en étant soumis à des modifications rapides des conditions environnementales. Sur les pistes les plus anciennes, en 30 ans, un tiers de la biomasse perdue lors de la construction a été reconstituée du fait de leur ré-végétalisation.

Dans le quatrième chapitre j'analyse l'extension du réseau des pistes, à l'échelle du paysage. J'ai utilisé pour cela une méthode originale, basée sur l'utilisation – pour la première fois en foresterie - de la formule dite « de l'espace vide » (empty space function). Cette formule résulte d'une extension aux deux dimensions d'une formule permettant d'analyser des processus ponctuels et présente l'avantage d'être mathématiquement bien définie. Appliquée au cas des pistes, elle permet de calculer la fragmentation des paysages. J'ai ainsi montré que la fragmentation des forêts dans les paysages définis comme « intacts » en 2000 (Intact Forest Landscapes ou IFL), a augmenté en général, et en particulier dans les concessions certifiées dans le cadre du FSC (Forest Stewardship Council). Je conclus en recommandant que l'aménagement forestier priorise la mise en réserve de la majeure partie de la concession forestière en assurant que les anciennes pistes restent inaccessibles.

Le chapitre de conclusion présente, tirées de ces résultats, des propositions pour l'aménagement forestier. Je montre que sur des coups d'exploitation récurrents, les anciennes pistes ne sont pas ré-ouvertes régulièrement. Après avoir évalué les bénéfices, les opportunités, les coûts et les risques liés à l'ouverture des pistes, je conclue que la ré-ouverture de ces pistes mérite une plus grande attention dans l'aménagement, et devrait être priorisée. La ré-ouverture pourrait épargner des superficies forestières et limiter les impacts négatifs sur la faune, en particulier liés à la chasse. A plus grande échelle, cela permettrait d'épargner des forêts encore peu ou pas exploitées, grâce à une intensification de l'exploitation dans des zones déjà perturbées. En conclusion, je vois l'aménagement des réseaux de pistes dans les forêts tropicales comme une planification active d'éléments transitoires dans le paysage, rendu complètement inaccessible jusqu'à leur réouverture. Les routes d'accès permanentes devraient être localisées à la périphérie de la forêt.

Mots clés

Ecologie routière, Forêt tropicale, Exploitation sélective, Dégradation, Répartition de l'usage de la terre, Régénération, Analyses spatiales, Aménagement du territoire

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List of acronyms

AAC	Assiette Annuelle de Coupe / Annual Allowable Cut
AFD	Agence Française de Développement
AGB	Above Ground Biomass
AIC	Akaike Information Criterion
BFT	Bois et Forêt des Tropiques
CAR	Central African Republic
CI	95% Confidence Intervals
CIB	Congolaise Industrielle des Bois
CIRAD	Centre de Coopération Internationale en Recherche Agronomique pour le Développement
CTFT	Centre Technique Forestier Tropical
DBH	Diameter at Breast Height
DRC	Democratic Republic of the Congo
ETM+	Enhanced Thematic Mapper plus
EU	European Union
EVI	Enhanced Vegetation Index
FAO	Food and Agricultural Organisation of the United Nations
FONASO	Forest and Nature for Society
FSC	Forest Stewardship Council
GIS	Geographical Information System
GLMM	Generalised Linear Mixed Model
GPS	Global Positioning System
IFL	Intact Forest Landscapes
IGN	Institute Géographique National
IUCN	International Union for the Conservation of Nature
LANDSAT	Land Remote Sensing Satellite Program
LMM	Linear Mixed Model
NDVI	Normalized Difference Vegetation Index
NGO	Non Governmental Organisation
NIR	Near-Infrared
NMDS	Non-Metric Dimensional Scaling
NPLD	Non-Pioneer Light Demander
OLB	Origine et Legalité des Bois
OLI	Operational Land Image

OSFT	Observation Spatiale des Forêts Tropicales
OSM	Open Street Map
PES	Payments for Ecosystem Services
REDD+	Reducing Emissions from Deforestation and Forest Degradation
RIL	Reduced Impact Logging
SB	Shade Bearer
SLC-off	Scan-Line Corrector failure
SPOT	Système Pour l’Observation de la Terre
SRTM	Shuttle Radar Topography Mission
SWIR	Short-Wave Infra-Red
TAH	Trans African Highway network
TM	Thematic Mapper
USGS	United States Geological Survey
WRI	World Resources Institute

Preface

Logging for timber in tropical forests (Figure 1) is a highly controversial activity. The underlying motivation for this thesis is that forest-rich countries cannot and should not be prohibited from using large parts of their territory, by declaring all remaining tropical forests protected areas. Accepting this precondition, I consider it better to cut some trees from a forest as long as it remains a forest, rather than completely clearing it to convert to agriculture. Given the prevalence of poor logging practices in many tropical countries, it seems crucial to assess *how* logging can be carried out in a less destructive way rather than discussing theoretically *if* it can be justified at all.

Figure 1 – Wheeled loader with log fork on a logging road in Republic of Congo

This approach does not, however, remain unchallenged. The NGO Global Witness even calls logging "The perfect crime" because, according to them, it allows companies in a destructive industry “to make the world believe that they are doing a good thing for countries that are rich in forests but otherwise poor” (Global Witness 2014). They are referring to European logging companies that receive support and financial aid from donors such as the World Bank and environmental organisations such as the World Wildlife Fund and the Forest Stewardship Council for their commitment to carry out sustainable forest management while exploiting tropical forest resources for their own short-term economic benefit. Crime seems an inappropriate word for an activity that is legal, but Global Witness argues from the ethical perspective that even legally exploited timber may not be legitimate from an ecological perspective.

Also in the scientific community doubts have been expressed whether logging in tropical forests can be justified at all and what role international trade should have in this (e.g. Bowles *et al.* 1998; Rice *et al.* 1997; Vincent 1992). The comment of an anonymous reviewer on one of the articles in this thesis makes the criticism quite clear:

"There is a broader point in arguing for slightly differing management of logging concessions that obscures the bigger picture. Few observers would advocate round-wood exports of timber form [sic] either never-logged or previously logged forest, as this activity, going on for 40yrs in the Congo Basin, hasn't brought improved local livelihoods, nor major income to national governments."

I am grateful that this issue has been mentioned by the reviewer as it concerns an important ethical question underlying the research presented in this thesis. However, I believe that the scope of this thesis is justified by the fact that national governments in Central Africa do allow logging - for whatever reasons they have. This is the reality faced by forest scientists, conservationists and planners. Logging activities are expected to continue in the future, independent of the origin of the capital to carry out these operations. Facing this realism, I consider it important to understand how current logging is impacting forests and how such threats can best be alleviated. Generally it seems that these debates have calmed down a bit in recent years, with the realization that the most important threat to tropical forests is not the selective extraction of trees but rather large-scale clearing for agro-industrial land use such as soy bean agriculture, palm-oil plantations or pastureland for cattle, promising high revenues for land-owners and states (Ferretti-Gallon & Busch 2014; Hosonuma *et al.* 2012; Rudel *et al.* 2009). Central Africa is still relatively untouched by such agro-industrial investments, but instead characterized by a long history of selective logging operations mostly at low intensities but with only hesitant commitments to social and ecological standards in exploitation practice being made in recent years (de Wasseige *et al.* 2014).

Roads have an outstanding role in public perception of tropical forest destruction. Images of the fishbone-like patterns of deforestation along the Transamazonian Highway in Brazil (Figure 2) are now part of the public collective memory and have become one of the symbols of global deforestation threats, in a similar way to the pictures of monotonous oil palm plantations and cattle pastures divided by a sharp line from the heterogeneous canopy of old-growth forests. Such images are a powerful visual representation of human dominance and destruction of tropical forests. However, as with all iconic images, this one creates the danger that a single case is used as the basis for generalisation to the complexity of tropical forest landscapes around the world - narrowing the imagination of the scientific community and its audience alike.

Figure 2 – Part of the Transamazonian highway in Pará, Brazil, an infamous symbol of how one road can destroy a whole forest. Detail from LANDSAT 8, dated 14 August 2015

This being the point of departure in the public mind-set about roads in rainforests means, for me, that it is where this thesis starts. Being aware of the highly emotional and symbolic importance of the subject, I consider it important to mention in advance what is *not* the aim of this thesis with its focus on logging roads in Central Africa. (i) I am not going to assess whether or not foreign companies should be allowed to perform extractive activities in tropical countries. (ii) I am not going to assess the benefits of building logging roads for local livelihoods or national governments. I agree that these are important issues that merit extensive research spanning the social, political and biological sciences. However, I am writing this thesis from a landscape planning perspective. This means that I am going to analyse changes in the landscape resulting from human pressures, as they can be detected at a large scale, and link this with ecological processes and management measures taking place on the ground. I hope ultimately to provide improved understanding and useful tools that can help conservationists to monitor, planners to regulate and also companies to improve logging operations.

This thesis is a compilation, with each chapter or chapter part already published or to be published as papers in scientific journals. However, all components are within the same theme (logging roads in Central African forests) starting with a general overview, then narrowing down to answer specific questions and finally expanding to wider applications and perspectives (Figure 3). The introduction (Chapter 1) consists of a literature review about logging roads in tropical forests (submitted to *Bois et Forêts des Tropiques*) and a short letter that I wrote to the editors of *Science* about the use of roads as indicators of forest degradation (unfortunately it has been rejected). The next two chapters analyse the persistence of logging roads based on two completely different datasets. Chapter 2, already published in *Ecosphere* (Kleinschroth *et al.* 2015), uses remote sensing of LANDSAT images and Chapter 3 (in press in *Journal of Applied Ecology*) is based on field data. From a wider perspective Chapter 4 approaches the development of roadless space in intact forest landscapes in Central Africa. This paper is submitted. The synthesis Chapter (5) presents different applications of the results including practical guidelines for practitioners. This chapter also contains a short opinion paper, suggesting that old logging roads be reopened rather than constructing new ones, which is in press in *Frontiers in Ecology and the Environment.* In the final Perspectives chapter (6) I emphasize what is missing in this thesis, in particular the social importance of road development, especially in areas with very little existing road infrastructure such as Central Africa.

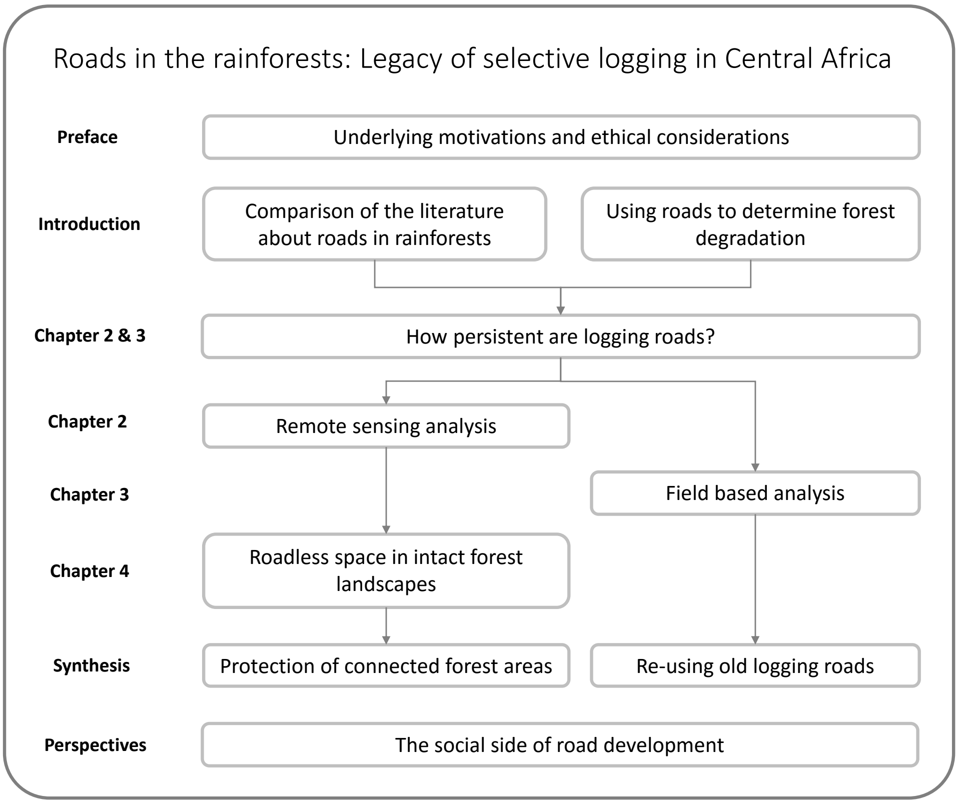

Figure 3 – Structure and connections of the thesis contents with the respective chapters on the left

Chapter 1

Logging roads in tropical forests: Synthesis of literature written in French and English highlights environmental impact reduction through improved engineering

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Abstract

Logging roads are considered important causes of forest degradation due to direct and indirect impacts on ecosystem functioning and biodiversity. Given that logging prevails in tropical forests around the world, effective road management is of crucial importance to reduce logging-related environmental impacts and the costs of logging operations at the same time. In a review we analysed how logging roads are addressed in the literature. We compared studies published over the past 65 years in the journal *Bois et Forêt des Tropiques* (BFT), written mostly in French, with a range of more recent articles from the databases Scopus and Web of Knowledge. Half of the articles on the subject in BFT were published already before 1972, while the generalist databases show a steady increase in the rate of publication since then, reaching a present peak. From the whole body of literature, we selected 126 articles, dealing with impacts and management of logging roads in tropical forests around the world, for critical appraisal. Articles in BFT were characterized by a strong focus on practical issues in forest road engineering, while many publications written in English were focussed on the identification of road-related impacts on forest ecosystems. Road-related environmental impacts stem from the loss of forest cover during their construction, the augmentation of edge effects on the forest, soil erosion and interference with wildlife, as well as the facilitation of access to the forest for hunting and agricultural colonization. Based on this review we present a list of recommended measures to reduce these impacts. We conclude that, despite the continuing attention paid to the subject, little is known about the long-term fate of logging roads in the forest landscape.

1.1 Background

Almost half of all remaining tropical forests in the world are subject to selective logging, with 20% having already been logged (Asner *et al.* 2009) and 400 million ha of natural tropical forests being in the permanent timber production estate (Blaser *et al.* 2011). Tropical forests are of global importance for carbon storage, biodiversity, food provisioning and other ecosystem services of great value for livelihoods. With less intact tropical forest available, these pivotal functions increasingly need to be delivered by logged forests that can retain high conservation values despite the logging disturbance (Edwards & Laurance 2013; Rutishauser *et al.* 2015). However, destructive and poorly planned logging practices persist throughout the tropics (Putz *et al.* 2008 2000) and there is an urgent need to better reconcile timber extraction with biodiversity conservation (Edwards *et al.* 2014b; Putz *et al.* 2012).

Global road networks have expanded rapidly over the past century, especially in tropical regions in recent years (van der Ree *et al.* 2015). In production forests roads are the dominant infrastructure for timber extraction. Historically, in forests adjacent to large enough rivers, rafts of logs were often floated down–river, but this means of transport is decreasingly used because it is slow and subject to a high rate of losses (Wilkie *et al.* 2000). Due to their spatial extent, construction and maintenance of roads is the most costly component of logging operations (Holmes *et al.* 2002a; Medjibe & Putz 2012) and also the element of logging in natural forests with the greatest environmental impacts (Laurance *et al.* 2009; Mason & Putz 2001). Because roads are the component of logging that is most easily detected, especially by remote sensing (Figure 1.1), roads are frequently used as inputs for observation and modelling of tropical land use and land

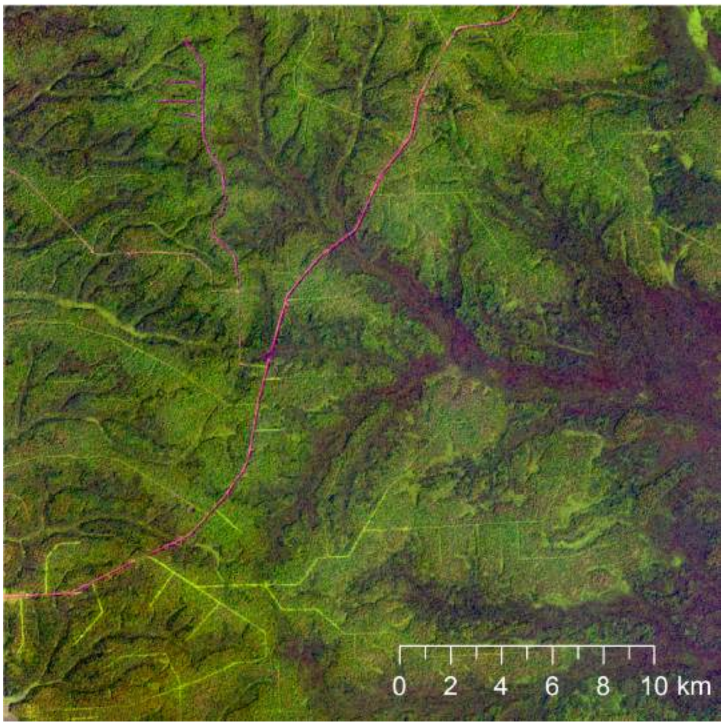

Figure 1.1 – Logging roads in the Northern Republic of Congo. Red colour indicates bare soils as on currently used roads; bright green indicates high photosynthetic activity as on abandoned roads with recovering vegetation. Extract of a LANDSAT 8 image, dated 7 January 2015.

cover change observation and modelling (Brandão & Souza 2006; Laporte *et al.* 2007; Rosa *et al.* 2014).

This chapter is a critical appraisal of the literature on the environmental impact of logging roads on natural tropical forests. Recent years have seen a rapid increase in articles addressing the impacts of roads on forest ecosystems. However, no previous review has adequately covered both the recent literature predominantly written in English and the previous French-language forestry literature, despite the long record of French science on tropical forest road management. We analysed the representation of logging roads in the literature over the long term with a particular focus on the question of how road-related impacts on forest ecosystems can be reduced.

1.2 Methods

1.2.1 Literature search

We used fixed search strings to generate search hits and used their number as an indication of coverage of the subject. For the French-language literature, we chose to limit the search to the journal *Bois et Forêts des Tropiques* (BFT) as it is the main publication for French language papers on this topic and it has a fully open-access archive dating back to 1947. This extensive archive is not fully covered by any of the common generalist databases and merits an analysis on its own. We used the search engine on the website http://bft.cirad.fr/ which does not accept Boolean operators or wildcards, therefore we successively applied the search strings: "route forestière", "piste forestière", "route exploitation" and "piste exploitation". For comparison we used the two most well-established databases that cover the widest scope of English-language literature, while focussing on peer-reviewed publications, Scopus and ISI Web of Knowledge. Google Scholar is also widely used to search for scientific literature as it also includes grey literature, books and reports. However, due to practical constraints a systematic assessment of this source was not possible and we only used it to select some influential publications outside peer-reviewed journals. In Scopus we used the search strings: "logging OR forest AND road AND tropic*" and in Web of Knowledge "(logging OR forest) AND road AND tropic*". According to their websites the Scopus archive dates back to 1966 and Web of Knowledge covers articles back to 1900, however, these databases are not transparent about the date since when articles from different sources are included. The total number of articles obtained by search hits were 57 for BFT, 656 for Web of Knowledge and 463 for Scopus. The first hit for the search strings in both of the databases covering English-language literature is in the year 1972. By the end of that year, 50% of all the identified articles in BFT had already been published, with a peak in the number of articles on the subject in the early 1950s. In Web of Knowledge and Scopus the subject was covered regularly only from the 1990s onwards, with a steadily increase in the number of articles, reaching almost 60 in Web of Knowledge in 2013 (Figure 1.2). These results are subject to bias due to the large differences in structure and coverage of the databases *versus* the single journal, BFT, and reflect the total number of papers published. We also emphasize that a wide range of forestry journals, including BFT, are only covered by Web of Science and Scopus from the 1990s onwards, therefore their earlier articles (and those from other professional forestry publications) are excluded from the searches using these two databases. The database CAB direct (http://www.cabdirect.org) has a more comprehensive coverage of the professional forestry literature, but is less used. We conducted a search only for comparison, which produced 704 hits using the same set of keywords as above. For a more systematic approach, a much wider search string would be necessary in order to capture all relevant forestry literature. Using the search string (logging OR forest*) AND (road*) AND (tropic* OR ...) and for "..." adding all tropical countries separated by OR (see Petrokofsky *et al.* 2015), generated 2721 results in CAB direct. However, even such an extensive search generates the first hits only for the year 1969, while in the

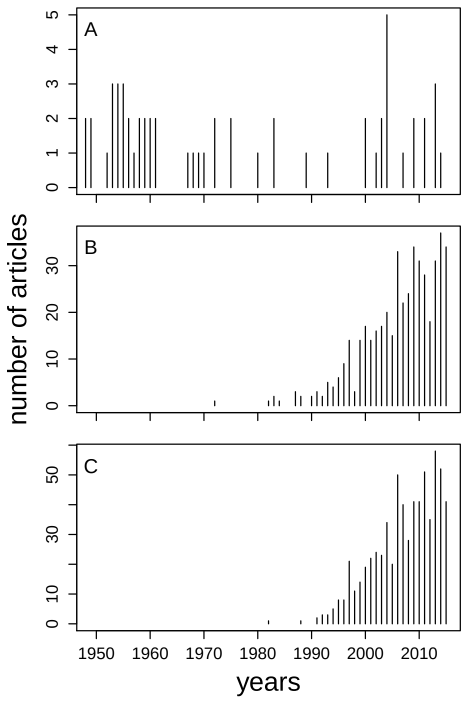

Figure 1.2 – Number of articles obtained by search hits for logging roads in tropical forests (exact search strings are given in the text) in the databases of (A) emphBois et Forêts des Tropiques, (B) Scopus and (C) ISI Web of Knowledge.

year 2013 alone there were 174. This partly reflects the limited coverage of older publications also in this database (earlier literature is well covered by the publication "Forestry Abstracts", but this could not be accessed by our on-line search) but it also shows the increasing amount of articles in general, and on this subject in particular.

Notwithstanding these methodological limitations in the search for articles, our results do indicate that researchers publishing in BFT addressed the subject of roads in tropical forests at the earliest stages of the development of the subject. We therefore consider it of great interest to include such publications in a critical appraisal comparing them with the dominant literature accessed by most people who use the common generalist databases such as Web of Knowledge and Scopus.

1.2.2 Selection of articles

For critical appraisal we selected 19 articles from BFT, 99 from the overall body of English-language peer-reviewed publications plus 5 books and 4 reports from searches in Google Scholar. Articles that addressed logging roads in tropical forests were selected by their relevance for the

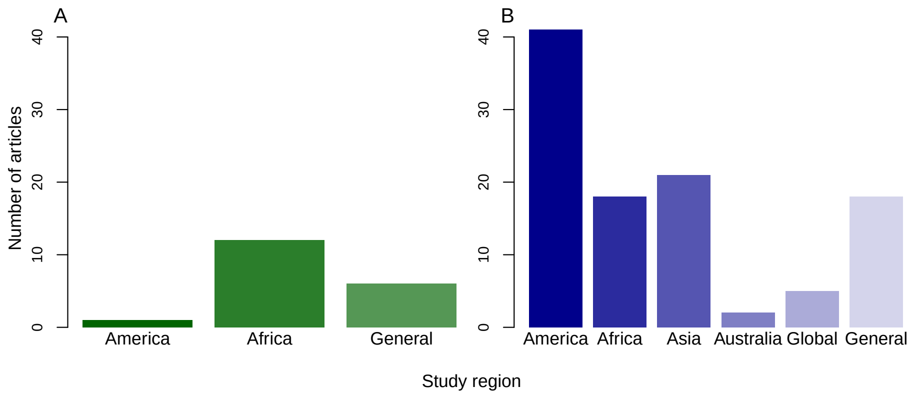

Figure 1.3 – Regional focus of articles (number of articles per continent, if applicable) selected for critical appraisal, comparing articles in *Bois et Forêt des Tropiques* (A) with English language literature (B). Global = Analyses carried out on a pantropical or global scale, General = General relevance without specific geographical reference.

disciplines ecology, engineering and geography. An overview of the selection criteria that were used for the screening of articles is given in Table 1.1. The term "logging road" is frequently used without further definition. We included only the articles reporting on roads that are built to allow wheeled vehicles to transport harvested logs from the landings, where they are loaded, out of the forest. We excluded roads constructed primarily for public use. The selection therefore includes primary (access) roads, which are mostly build for permanent use, as well as secondary (dead-end) roads, generally built for use over a limited time during a single timber harvesting operation. This definition excludes skid trails designed for use by tracked vehicles, which are narrower and thus often do not form a continuous opening of the canopy. Due to constraints of time and resources, the choice and application of selection criteria were not independently tested by a second person, hence their reproducibility might be limited.

The geographical focus of the articles differed between the two literatures. Whilst the French-language BFT papers were mostly focused on Francophone African countries, a majority of the English-language articles focused on tropical America, in particular the Amazon. Only half as many English-language articles focused on Asia and again fewer on Africa, with a few on tropical Australia (Figure 1.3).

Table 1.1 – Inclusion and exclusion criteria for articles to be considered for critical appraisal, listed in hierarchical order.

	Inclusion criteria	**Exclusion criteria**
Language	English, French (only in BFT)	Any other language, other journals in the French language
Object	Roads and road networks	
Location	Pan-tropical (Central and South America, Africa, South-East Asia, Australia)	Non-tropical
	Closed canopy tropical forests used for timber exploitation	Tree plantations after clearcutting, shrublands, savannas, wetlands
Principal utilization	Wheeled vehicles transporting timber	Skidding (log yarding), public transportation
Type	Primary roads: permanently maintained, providing principal access to the forest	
	Secondary roads: mostly dead-end roads, connecting logging sites with primary roads, abandoned after use	
Questions and applications	Forest engineering: Layout, design, construction, maintenance, management	Purely concerning economic and social development or land use policy
	Ecology: interactions with wildlife and forest ecosystems, direct and indirect impacts, persistence, impact reduction	Logging impacts that are not directly linked with roads (e.g. timber species population and recruitment issues)
	GIS and remote sensing: detection, characterization, spatial distribution	Mentioning roads only as one of many factors in connection with forest degradation and deforestation

1.3 Critical appraisal

1.3.1 Technical advice for forest exploitation

The very first article in BFT that mentioned roads in Central African forests (Steinmann 1948), was written with the connotation of adventure in exploring the forest as unknown territory in order to gain access to forest resources in the French colonies. Over the next few years later the articles in BFT became very specific in giving technical advice for road planning, building and maintenance in order to ensure efficient logging operations. Detailed descriptions of machines used for construction, maintenance and transport were given (Le Ray 1958; Tuffier 1954) but also a wide range of recommendations for road engineering were presented and discussed. Of major importance here was the construction of roads adapted to the landscape, e.g. fitting a road into the terrain, contouring the shape of the road surface, implementing drainage systems and designing river crossings (Allouard 1954a; Esteve & Lepitre 1972; Le Ray 1956 1960). Decades later, and without making reference to these articles, several very similar ideas and recommendations were presented in a book in English on forest road operations in the tropics (Sessions 2007), showing that most of these engineering principles introduced more than 60 years previously are still considered to be “good” practice. Early articles also considered the planning strategy of the overall road network and the optimization of the layout, with maps and schematic plans given as examples (Allouard 1954b; Krzeszkiewicz 1959; Le Ray 1959). The average skidding distance of one km in Central Africa, which is the main variable that influences road spacing in the landscape, has not changed since then (*personal observation*). These articles were based on the primarily objective of maximizing the number of trees that can be reached with the least effort and costs for road building. However, they also mentioned that these measures would help to reduce the extent of damage to the forest. For most subsequent articles on this subject, in other journals (Dykstra & Heinrich 1996; FAO & ATIBT 1999; Gullison & Hardner 1993; Johns *et al.* 1996; Picard *et al.* 2006; Schulze & Zweede 2006), the primary objective changed towards impact reduction, but the recommended practices remained very similar.

1.3.2 Direct impacts of roads on tropical forests

We found few detailed analyses of the ecological impacts of logging roads in articles published in BFT. Estève (1983) quantified the destruction of forest cover for logging-related infrastructure in Central Africa and South America and concluded that with a rate of only 5% destruction the ecological value of the forest remained largely unchanged. In an African logging concession, roads and log landing sites accounted for only 0.8% of the forest area (Durrieu de Madron *et al.* 2000). However, the majority of the English-

Figure 1.4 – Newly constructed logging roads in south east Cameroon and northern Republic of Congo. Left: Primary road, providing permanent access to the forest. Right: secondary (dead-end) road built for temporary use to collect timber from log landings (here stored on the road side).

language articles published over the last 25 years give a strongly contrasting perspective, describing a variety of road-related threats to forest ecosystems with potentially detrimental effects to their ecological functioning at various scales.

The amount of forest cover cleared (Figure 1.4) and thus biomass lost for road building has been raised as an issue in terms of local-scale impacts (Gideon Neba *et al.* 2014; Olander *et al.* 1998). However, strong regional differences are reported, with a notably high average value of 17% stand disturbance by roads and skid trails in Malaysia (Pinard *et al.* 2000). Even if only a small proportion of the forest cover is cleared for road building (as in most of Central Africa and Amazonia), negative effects might reach much further. Edge effects can lead to the death of big trees (Laurance 2000b) and the desiccation of forests due to enhanced evapo-transpiration in adjacent forest areas (Briant *et al.* 2010; Fraser 2014; Goosem 2007; Kunert *et al.* 2015). Together with large amounts of debris (left behind after clearing) as a potential fuel, roads can thus increase the vulnerability of the forest to fires (Nepstad *et al.* 2001; Uhl & Kauffman 1990).

Road construction drastically changes the forest habitat, not only by removing vegetation but also by altering soil functions through removal of top soil, application of external materials and heavy mechanical compaction (Donagh *et al.* 2010). The most severe effect of soil exposure and compaction is often erosion (Douglas 2003; Malmer & Grip 1990), which in combination with heavy tropical rainfall can remain a problem for more than ten years after logging (Clarke & Walsh 2006). This results in the loss of soil material on and around roads and the accumulation of sediment in streams and rivers (Gomi *et al.* 2006; Negishi *et al.* 2008; Ziegler *et al.* 2007). Together with other hydrological impacts, e.g. damming of water courses through inadequately constructed river crossings this can lead to serious deterioration of the ecosystem by changing the physical and chemical characteristics of the water (Bruijnzeel 2004; Connolly & Pearson 2007; Trombulak & Frissell 2000). This can have a direct impact on local communities who depend on the ecosystem service of clean drinking water from streams (Mandle *et al.* 2015). Many of the articles examining road-related impacts also present possible mitigation measures that we discuss in detail below.

Roads in forests directly interfere with animal populations through road kill (Clements *et al.* 2014; Laurance *et al.* 2009) but also by influencing their movement and behaviour (Chazdon *et al.* 2009; Hoeven 2010; Lees & Peres 2009). Negative effects of roads have been shown on small mammals (Malcolm & Ray 2000), birds (Develey & Stouffer 2001; Laurance & Gomez 2005), elephants (Blake *et al.* 2008) and dung beetles (Hosaka *et al.* 2014). This has been associated with habitat changes and human activity but increased noise levels can also have an impact (Laurance 2015). However, roadsides and abandoned roads can also attract animals due to higher abundance of herbs as food sources, as has been shown for gorillas (Matthews & Matthews 2004). Puddles and ditches resulting from compacted soils on logging roads have been reported to be a suitable reproduction site for turtles (Ernst *et al.* 2014). An overview of the varying effects of roads on different groups of species is given by van Vliet & Nasi (2007) showing, for example, that elephants are more frequently found in proximity to roads and settlements while certain wild ungulates show strong patterns of road avoidance.

1.3.3 Indirect impacts of roads on tropical forests

Arguably the biggest threat resulting from logging roads in the tropics is that they grant access to the forest interior for other land uses. The presence of roads facilitates illegal and uncontrolled logging activities (Laurance & Balmford 2013; Obidzinski *et al.* 2007) and the probability of logged areas being deforested is highly dependent on distance from major roads (Asner *et al.* 2006). This is mostly because logging roads are used successively for encroachment by farmers who colonize new areas for slash-and-burn agriculture (Johns *et al.* 1996; Mertens & Lambin 2000; Pfaff *et al.* 2007; Reid & Bowles 1997). However, this process varies depending on human population density, soil quality and topography (Cropper *et al.* 1999), as well as market access and tenure regulations (Chomitz & Gray 1996), and is often linked with official re-designation of roads for public use or even large-scale programs with incentives for colonization (Barber *et al.* 2014; Nepstad *et al.* 2001). With increasing disturbance intensity this can lead to feedback loops resulting in deforestation or severe degradation at larger scales (Laurance *et al.* 2002; Malhi *et al.* 2014).

Figure 1.5 – Hunted duiker along a logging road in Cameroon.

In the absence of appropriate landscape planning, over the long-term some roads initially built for logging have developed into major public roads and can even be linked with the conversion to large-scale agro-industrial agriculture and pastoralism. This has been reported for Latin America and South-East Asia for cattle grazing, soy-bean production and oil-palm plantations (Fearnside 2007; Laurance & Balmford 2013; Reid & Bowles 1997). However, the reason why logged forests become vulnerable to such conversions can only indirectly be attributed to the presence of roads. It is more linked with the loss in short-term economic value and a widespread underestimation of the ecological importance of production forests (Edwards *et al.* 2014b; Gaveau *et al.* 2013).

A less visible form of forest degradation resulting from roads is the depletion of wildlife populations through unregulated hunting that has even resulted in "empty" forests (Laurance *et al.* 2006; Poulsen *et al.* 2011; Redford 1992; Robinson *et al.* 1999). In Central Africa especially, bushmeat provides the most important source of protein for most forest-dependent communities, making hunting an essential activity for human nutrition that has been practiced for a long time (Figure 1.5). However, the presence of extensive road networks has led to a process of specialization of market hunters linked to a longer transport chain and increased quantities of extracted bushmeat being supplied to meet the increasing demand in urbanized areas further away from the forest (Nasi *et al.* 2008; Wilkie & Carpenter 1999; Wilkie *et al.* 2000). Even logging vehicles are frequently used to transport hunters, weapons and game, thus increasing the radius of defaunation around settlements deeper into the forest (Poulsen *et al.* 2009).

Roads can also facilitate biological invasions in tropical forests. Dispersal by trucks and other logging vehicles has been shown to be the main driver for the spread of exotic tree (Padmanaba & Sheil 2014), ant (Walsh *et al.* 2004) and grass (Veldman & Putz 2010) species.

1.3.4 Reducing the impacts of logging roads

The potential problems with roads in tropical forests have long been appreciated from a forest management perspective and so there has been a parallel set of publications focused on the development of engineering techniques designed to minimise these problems. These are well represented in both the French- and English-language literatures (Table 1.2).

Improved road planning, construction and maintenance has been a central element in the development of reduced-impact logging (RIL) guidelines (Pinard *et al.* 1995) and in the FAO model code of forest harvesting practice (Dykstra & Heinrich 1996). Effective road planning in order to reduce residual stand damage and loss of biomass, as described in BFT in the 1950s, was included as a key component of RIL (Putz *et al.* 2008). Another important recommendation is to reduce the clearing width of road corridors (Putz & Romero 2015; Sist 2000b). Especially in Central Africa, there is still a widespread belief among forest managers that forest clearing on both sides of the road is necessary to let the sun dry the road surface (Sessions 2007). However it has already been emphasized by (Allouard 1954a) that a well-maintained and drained road does not require a wide open canopy. Also, the need to build roads fitted to the topography in order to avoid soil erosion on the road surface (Negishi *et al.* 2008) has long been articulated (Le Ray 1956).

With a stronger focus on biodiversity conservation, the set of impact-reduction measures has recently been augmented. This includes the declaration of set-asides from logging in high conservation-value areas as well as measures to reduce the fragmenting effect of roads on animal habitats (Clements *et al.* 2014; Goosem 2007). Given the problems with hunting and encroachment, control of access has been identified as a crucial aspect of road management. This requires guarded barriers at strategic points in the permanent road network but also the closure of roads after harvest (Applegate *et al.* 2004; Bicknell *et al.* 2015; Mason & Putz 2001). However, wherever local communities do not accept such measures, it becomes difficult for logging operators to enforce them. Since RIL standards have been published, numerous studies have been carried out subsequently comparing the effectiveness of RIL with that of conventional logging, generally emphasizing the usefulness of such measures including road building standards (Ezzine de Blas & Ruiz Pérez 2008; Feldpausch *et al.* 2005; Healey *et al.*

2000; Medjibe & Putz 2012; Pereira *et al.* 2002).

Table 1.2 – Logging-road-related environmental problems and measures to mitigate such impacts. Each measure is only listed once, although it could also be useful in the context of other problems. A selection of the most relevant references is given for each measure.

Road-related environmental problems	**Measures to reduce impacts**	**References**
Forest clearing for road construction (carbon emissions, loss of habitat)	Minimize road length by optimizing the layout (to reach the resource via the shortest path)	Gullison & Hardner (1993); Johns *et al.* (1996); Le Ray (1959); Picard *et al.* (2006); Schulze & Zweede (2006)
	Minimize road length by finding the optimal ratio between lengths of roads and skid trails	Dykstra & Heinrich (1996); Krzeszkiewicz (1959); Sessions (2007)
	No road construction in high conservation-value areas	Durrieu De Madron *et al.* (2011); Healey *et al.* (2000); Sist *et al.* (1998)
	Allow changes in road alignment to avoid large trees	Le Ray (1959); Sessions (2007)
Edge effects: desiccation, wind exposure, death of large trees	Reduce the width of forest clearing for road construction (on average 10 m, taking solar angle and exposure to wind into account)	Allouard (1954a); Dykstra & Heinrich (1996); Feldpausch *et al.* (2005); Laurance & Gomez (2005); Laurance *et al.* (2009); Sist (2000a)
Soil erosion (and the deterioration of water quality through sedimentation)	Adapt road routing to the topography (location on top of ridges and across slopes)	Allouard (1954b); Esteve & Lepitre (1972); Le Ray (1956); Pinard *et al.* (1995)
	Limit the road gradient and the length of downhill runs	Allouard (1954a); Le Ray (1956); Negishi *et al.* (2008); Ziegler *et al.* (2007)
	Ensure drainage through road camber, roadside ditches and cross-drains	Allouard (1954a); Dykstra & Heinrich (1996); Le Ray (1956); Putz *et al.* (2008); Sessions (2007); Sist (2000b)
	Stabilize the road surface with laterite	Allouard (1954b); Sessions (2007)

Road-related environmental problems	**Measures to reduce impacts**	**References**
	Good engineering practice in fitting road alignment to the terrain and protect slopes (e.g. minimise high risk excavations of side slopes)	Allouard (1954b); Dykstra & Heinrich (1996); Le Ray (1956); Sessions (2007)
Physical alteration of streams	Limit amount of stream crossings	Clarke & Walsh (2006); Le Ray (1959)
	Apply good engineering practice in building culverts, bridges and fords	Allouard (1954a); Douglas (2003); Sessions (2007)
	Place buffer zones around streams and wetlands	Applegate *et al.* (2004); Pinard *et al.* (1995)
Road kill and behaviour change of animals	Set up road crossing infrastructure (signs, speed bumps, bridges, culverts)	Clements *et al.* (2014); Laurance *et al.* (2009)
	Ensure overhead canopy connections (green bridges)	Goosem (2007); Sessions (2007)
	Set and control speed limits	Allouard (1954a); Laurance *et al.* (2006); Sessions (2007)
	Respect habitats of endangered species in road planning	Clements *et al.* (2014); van Vliet & Nasi (2007)
	Limit number and weight of logging vehicles	Allouard (1954a); Sessions (2007)
	Adapt roadside vegetation to animal preferences	Hoeven (2010)
Facilitation of hunting	Control access to currently used roads	Mason & Putz (2001); van Vliet & Nasi (2007)
	Close secondary roads after harvest with physical barriers and removal of stream crossings	Applegate *et al.* (2004); Bicknell *et al.* (2015); Sist *et al.* (1998); van Vliet & Nasi (2007)
	Prohibit the transport of hunters and bushmeat with logging vehicles	Poulsen *et al.* (2009); Robinson *et al.* (1999); Wilkie *et al.* (2000)
Agricultural colonization	Plan and regulate land-uses, provide alternatives for settlers	Chomitz & Gray (1996); Dykstra & Heinrich (1996); Laurance *et al.* (2014); Mertens & Lambin (2000)

Figure 1.6 – Abandoned logging roads, closed with a log to block access one year after exploitation in south east Cameroon (left) and with dense herb cover and regenerating trees 14 years after abandonment in northern Republic of Congo (right).

Forest regeneration after exploitation is of crucial importance for sustainable forest management (Karsenty & Gourlet-Fleury 2006; Kleinschroth *et al.* 2013; Zimmermann & Kormos 2012). Given that most secondary logging roads are only temporarily used, they do provide a potential site for tree regeneration after abandonment (Figure 1.6). However, especially in areas where high volumes of timber are harvested such as in the dipterocarp forests of South-East Asia, reduced levels of regeneration have been reported on abandoned roads and skid trails due to unfavourable soil conditions (Pinard *et al.* 1996 2000; Zang & Ding 2009). Also, in more urbanized areas, lower levels of forest recovery have been recorded with proximity to roads (Crk *et al.* 2009). In contrast, for regions with low intensity logging regimes, logging roads and strip clear cuts have been associated with enhanced levels of regeneration of light-demanding timber species (Fredericksen & Mostacedo 2000; Hartshorn 1989; Nabe-Nielsen *et al.* 2007; Swaine & Agyeman 2008). Road edges, those areas that have been cleared during road construction to let the sun dry the surface, are particularly suitable microhabitats for recruitment of timber species (Doucet 2004; Guariguata & Dupuy 1997).

1.3.5 Characterizing the spatial distribution and coverage of logging roads

Highly selective logging at low densities, as occurs in most of Central Africa and Amazonia, is a form of cryptic disturbance which, in contrast to full deforestation, can only be detected marginally or not at all with conventional remote sensing techniques on larger scales (Peres *et al.* 2006). Due to their linearity and connectedness, roads are the only components of such logging activities that are detectable on medium- to high-resolution satellite images. Articles in BFT were among the first to make use of this finding and suggested the use of logging roads as indicators of the extent of logging disturbance in tropical forests (Bourbier *et al.* 2013; Gond *et al.* 2003; Mayaux *et al.* 2003). Despite some technical drawbacks (de Wasseige & Defourny 2004), it is now the de facto standard across all tropical regions to use roads as indicators for human dominance of tropical forests (Asner *et al.* 2004ab 2009; Gaveau *et al.* 2014; Hirschmugl *et al.* 2014; Laporte *et al.* 2007; Souza *et al.* 2005). The spatial distribution, i.e. the extent and density, of road networks can be used to model human influences on tropical forests at larger scales (Ahmed *et al.* 2013a 2014 2013b; Arima *et al.* 2008; Bell *et al.* 2012; Mertens *et al.* 2001). It also served as an important input to define the intactness of forest landscapes (Potapov *et al.* 2008) and the identification of priority road-free areas at a global scale (Laurance *et al.* 2014).

1.4 Contrasting trends in the literature

Assessment of the literature included in this review reveals two main underlying agendas for these studies that can be roughly classified into conservation approaches versus forest management approaches. Dominant parts of the recent literature found in the generalist databases Web of Knowledge and Scopus are focussed on the negative impacts of industrial-type logging and reinforce the long-standing bad reputation of export-driven timber harvesting in tropical countries (e.g. Bowles *et al.* 1998). Only recently, facing the overwhelming occurrence of logging in tropical forests, have publications started to address the ecological value of logged forests that shows the need for them to be protected from further conversion into oil-palm plantations or other agricultural land (e.g. Edwards *et al.* 2011). Conversely, almost all the reviewed articles in BFT adopted a much more pragmatic approach, without expressing any doubts openly about the continuation of logging activities. The history of BFT cannot be disentangled from French colonial history and its' founding institution, the Centre Technique Forestier Tropical (CTFT). The initial colonial motivation of efficiently organizing forest exploitation in overseas forests was later translated into development cooperation (Bonneuil & Kleiche 1993). However, no change occurred in the adherence to the traditional (eurocentric) principles of sustainable forestry and the aim to promote this in collaboration with a range of stakeholders in the field. Irrespective of the motivations behind the historical literature, it contains a high standard of engineering recommendations and the resulting practices mostly persist to the present day. Knowledge of this historical legacy from the literature is crucial in understanding the development of today's logging practices. Lessons learned in the 1950s should not be forgotten, but rather fed into modern evaluation and improvement of logging activities.

1.5 Identification of knowledge gaps

We have reviewed a large body of literature about logging roads in tropical forests, mostly focussing on immediate direct and indirect environmental impacts and on management techniques designed to mitigate these. However, given the history of more than half a century of industrial-scale logging operations it is somewhat surprising that the long-term fate of logging road networks remains unknown, with insufficient attention paid to road abandonment and subsequent forest recovery. This may be linked to the fact that large formerly-logged areas in Latin America and South East Asia are now deforested. However, in Central Africa this is not the case. Here, only a small proportion of logging road networks is maintained in a constantly open state due to the costs and the obligation for many forest concessions to close secondary roads after exploitation. Little is known about the persistence of road networks in the overall forest landscape or about the long-term successional trajectory on abandoned forest roads, especially in Central Africa. Such long-term characterization of forest road networks can help in the development of much needed strategies for post-logging silviculture and should be taken into account when determining forest degradation based on road networks, for example in the context of the REDD+ programme (reducing emissions from deforestation and forest degradation).

We feel that current definitions of intactness or roadlessness of forest landscapes do not do justice to the complexity of the interactions between roads and forests when they are simply based on the application of a fixed buffer distance around all roads that were ever detected. A new understanding of the temporal and spatial dynamics of forest road networks is urgently needed for initiatives that try to reconcile forest certification with the protection of intact forest landscapes. The long-term management of road networks should provide a crucial step towards the anticipated goal of supra-regional landscape planning across the tropics (Lewis *et al.* 2015).

1.6 Road dominance of tropical forests

Reply to Lewis, S.L., Edwards, D.P. & Galbraith, D. (2015). Increasing human dominance of tropical forests. *Science*, 349, 19–73.

In their insightful review "increasing human dominance of tropical forests" Lewis *et al.* (2015) issue an important warning to the world and also challenge the scientific community to better assess tropical forest degradation in the context of spatio-temporal dynamics in human-environment systems.

We are not there yet when it comes to pantropical quantification of forest degradation. Recent estimates (Mercer 2015) cited by Lewis et al. are based on a map (http://www.wri.org/resources/maps/global-map-forest-landscape-restoration-opportunities) evaluating restoration opportunities on global 250 m resolution satellite imagery (Laestadius *et al.* 2011). But how reliable are estimates of forest degradation based on such coarse resolution? The most common way to assess disturbance in tropical forests is by using roads as indicators (Laporte *et al.* 2007). Lewis et al. cite (Laurance *et al.* 2014) that by 2050, >25 million km of roads are predicted to be built across the tropics. Yet the original source for this statement was a forecast for paved road lane-kilometers to be built worldwide (Dulac 2013) and it is difficult to extrapolate these predictions to tropical forests, where predominantly unpaved roads are built. The cited map of "Intact Forest Landscapes" (Potapov *et al.* 2008) is based on the extent of roads and settlements derived from Landsat images (of 30 m resolution) until the year 2000. However, since then a lot of new roads have been built, especially for logging, while others have become undetectable due to abandonment and subsequent forest regeneration (Kleinschroth *et al.* 2015). Thus, road networks in tropical forests are highly dynamic in space and time. Using roads as indicators of forest degradation needs to take their varying persistence in the landscape into account. Monitoring transience of roads in tropical forests along with effective management of accessibility will provide crucial evidence for the goal of "development without destruction" advocated by Lewis et al., e.g. through large-scale landscape planning.

Chapter 2

Legacy of logging roads in the Congo Basin: how persistent are the scars in forest cover?

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Abstract

Logging roads in the Congo Basin are often associated with forest degradation through fragmentation and access for other land uses. However, in concessions managed for timber production, secondary roads are usually closed after exploitation and are expected to disappear subsequently. Little is known about the effectiveness of this prescription and the factors affecting vegetation recovery rate on abandoned logging roads. In a novel approach we assessed logging roads as temporary elements in the forest landscape that vary in persistence depending on environmental conditions. We analyzed road persistence during the period 1986-2013 in adjacent parts of Cameroon, Central African Republic and Republic of Congo. Three successive phases of road recovery were identified on LANDSAT images: open roads with bare soil, roads in the process of revegetation after abandonment and disappeared roads no longer distinguishable from the surrounding forest. Field based inventories confirmed significant differences between all three categories in density and richness of woody species and cover of dominant herbs. We used dead-end road segments, built for timber exploitation, as sampling units. Only 6% of them were identified as being re-opened. Survival analyses showed median persistence of four years for open roads before changing to the revegetating state and 20 years for revegetating roads before disappearance. Persistence of revegetating roads was 25% longer on geologically poor substrates which might result from slower forest recovery in areas with lower levels of soil nutrient content. We highlight the contrast amongst forests growing on different types of substrate in their potential for ecosystem recovery over time after roads have been abandoned. Forest management plans need to take these constraints into account. Logging activities should be concentrated on the existing road network and sites of low soil resource levels should be spared from business-as-usual exploitation.

2.1 Introduction

Logging roads are often associated with forest degradation through fragmentation and by opening up the forest for subsequent encroachment by hunters, illegal loggers and farmers (Newman *et al.* 2014; Wilkie *et al.* 2000). Building a road into an unexploited rainforest has been compared to opening Pandora's box: a small intervention with escalating consequences for the forest ecosystem (Fraser 2014; Laurance *et al.* 2009). This, and the amount of forest clearing for the road itself, makes road building the most persistent form of forest damage associated with selective logging (Gullison & Hardner 1993). Accordingly, logging road networks have been used as a proxy to assess the extent of selective logging disturbance in tropical forests (Asner *et al.* 2002 for the Amazon, Laporte *et al.* 2007 for the Congo Basin).

Major logging operations in the Congo Basin take place in industrial concessions (Nasi *et al.* 2012; Ruiz Perez *et al.* 2005). An increasing proportion have produced forest management plans designed to ensure sustainability of their logging operations (Bayol *et al.* 2012; Karsenty *et al.* 2008). One important rule of sustainable forest management requires that logging roads are closed after harvesting (Putz *et al.* 2008). Therefore the forest contractor must, for example, erect physical barriers to stop road access by vehicles or remove temporary stream crossings at the end of a harvesting period (Applegate *et al.* 2004). By right, this rule should be applied in most parts of the study area, the Sangha river catchment, because it is included as a prescription in the forest management plans implemented in this area (Nicolas Bayol, co-author of several forest management plans in the region, *personal communication*). However, there has not yet been an evaluation of how long it takes until forest cover is reestablished after road abandonment and which site-specific drivers prolong persistence of logging roads.

Forest recovery after disturbance varies depending on local site conditions including soil fertility (Chazdon 2014; Guariguata & Ostertag 2001). For the northwestern Congo Basin it has been shown that the functional diversity of tree communities is heavily influenced by geological substrate (Fayolle *et al.* 2012). The range of substrates includes those that are sandy and of low fertility which are hypothesised to support slower recovery from deforestation and degradation (Chazdon 2003; Gourlet-Fleury *et al.* 2011). However, none of the forest management plans that are currently active in this region take account of these site conditions when assigning annual cut zones and potentially vulnerable areas (N. Bayol, *personal communication*).

Forest regeneration on roads is not only of major interest for nature conservation but also from a commercial perspective. Vegetation cover protects the road surface from erosion damage, a frequent and severe problem on logging roads in forests with high amounts of rainfall (Laurance & Useche 2009; Negishi *et al.* 2008; Sessions 2007). If roads are not re-opened for further harvesting operations, forest recovery on the road may even be of long-term commercial value for timber production if it eventually leads to regrowth of harvestable timber trees on the land area occupied by the road. Logging road networks can be classified into three hierarchical levels (Sessions 2007): (1) principal roads that form permanent transport links between forest roads, public roads and markets, (2) primary roads forming the basic structure of the forest road network and (3) secondary (feeder) roads that connect log landings to the primary forest roads. Secondary roads are the ones that are usually abandoned after logging operations (Malcolm & Ray 2000) and therefore no surfacing or sub-surface drainage operations are carried out (Sessions 2007). Due to these predictable patterns of use frequency and duration, secondary roads are particularly suitable for the study of spontaneous forest recovery processes.

The strategic choice between land sparing and land sharing strategies applies equally to timber production as it does to agriculture (Edwards *et al.* 2014b; Healey *et al.* 2000). To inform this forest management decision, a better understanding of how forest recovery on roads depends on site-specific factors will help identify more and less resilient forest areas. We therefore addressed two central study questions: (1) how long does it take until forest cover is re-established after secondary road abandonment and (2) what are the main biophysical and geographical factors that affect secondary road persistence?

2.2 Methods

2.2.1 Study area

The study region is in the catchment of the Sangha River, a major tributary in the north west of the Congo River basin. The specific study area was selected based on imagery collected over two scenes of the LANDSAT satellite missions 7 ETM+ and 4/5 TM (30 m pixel size). We chose the scenes located in path 182, rows 58 (centered at 2° 54 N, 16° 21' E) and 59 (1° 27' N, 16° 3' E) with the Sangha-Trinational conservation complex in the center to cover a range of different countries, geological substrates and logging histories. The main towns are Nola, Central African Republic (CAR) and Ouesso, Republic of Congo (Figure 2.1). The surface captured by the sensor has an extension of about 335 by 180 km (60 000 km^2). The vegetation is characterized by mixed moist semi-evergreen *Guineo-Congolian* forests (White 1983). The mean annual rainfall varies between 1400 and 1700 mm with three to four dry months (Hijmans *et al.* 2005) and the altitudinal range is between 330 and 745 m. Parts of three countries were included: Republic of Congo (40 877 km^2), CAR (10 766 km^2) and Cameroon (10 297 km^2). Around 16% of the area constitutes national parks (IUCN category II) and 5% special protection areas (IUCN category IV), established between 1963 and 2001. Sixty-seven percent of the study area is occupied by active logging concessions and, of their area, 92% has had a management plan implemented during the last 10 years (WRI & MDDEFE 2012; WRI & MEFCP 2010; WRI & MINFOF 2012).

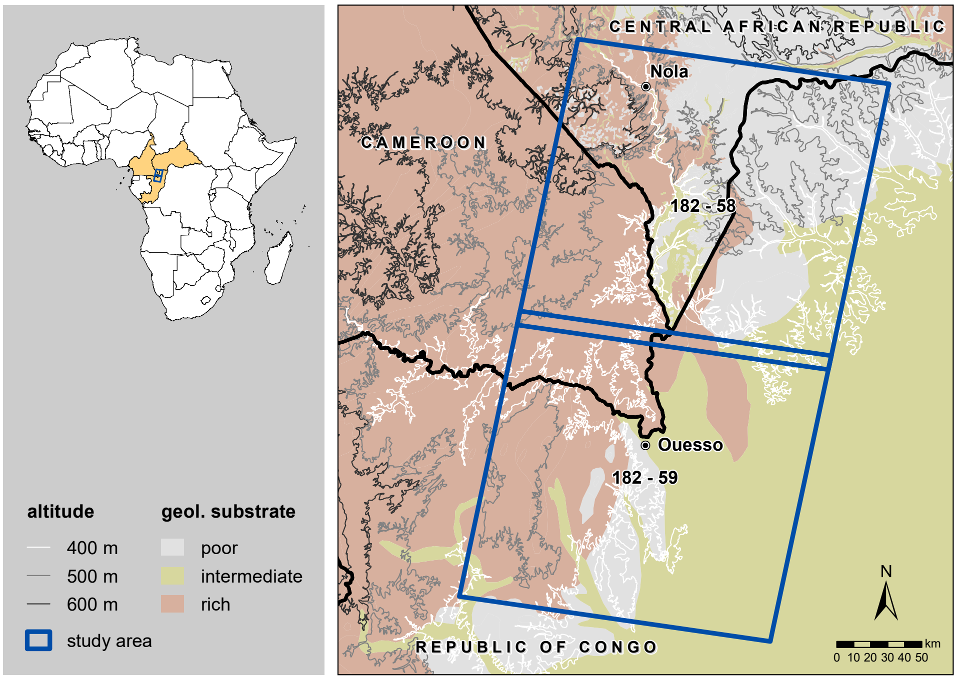

Figure 2.1 – Area of the study in the north-western Congo Basin, determined by the footprint of LANDSAT scenes path 182, rows 58 and 59 (blue boxes). Geological substrates according to their nutrient content type are shown using a color scale and 100 m contour lines are shown in a grey scale.

2.2.2 Temporal dynamics in the road network

We analyzed the dynamics of road segments from first appearance to disappearance (due to re-establishment of forest cover) based on a time series of LANDSAT images. We classified road condition into three categories. (i) Open roads were indicated by bare soil (lacking vegetation cover) due to current vehicular traffic (e.g. due to logging activity), or a lack of subsequent recovery. (ii) In contrast, revegetating roads were in the process of re-establishment of vegetation cover after logging activities and vehicular traffic have stopped. (iii) Disappeared roads could no longer be distinguished from the surrounding forest in the LANDSAT image. We included all images from 1986 to 2013 provided by the USGS National Center for Earth Resources Observation and Science (http://www.glovis.gov). Due to limits in image availability and quality, we clustered available images in seven four-year observation intervals (Table 2.1).

Table 2.1 – Number of LANDSAT scenes of different dates in two locations (path/row) providing data in each of two spectral bands (red and near-infrared, NIR) during each four-year observation interval used for manual delineation of road networks.

	Path/Row			
	182/ 58		182/ 59	
Observation interval	Red	NIR	Red	NIR
1986-1989	3	6	5	4
1990-1993	1	1	1	1
1994-1997	2	4	3	4
1998-2001	5	7	4	3
2002-2005	6	6	6	3
2006-2009	11	6	5	4
2010-2013	5	7	5	7

Manual delineation is a common procedure to detect roads on satellite images of closed forest landscapes (Ahmed *et al.* 2014; Brandão & Souza 2006; Laporte *et al.* 2007). This way of digitizing forest roads allowed us to clearly differentiate between roads and other linear features such as rivers by taking into account patterns such as linearity, connectivity and bifurcation angles. In a few doubtful cases comparison with a hydrological map proved to be helpful. The novelty in our approach is to differentiate categories of roads, depending on their vegetation cover in relation to the surrounding forest. Based on the contrasting reflective properties of bare soil ("open"), pioneer vegetation with high photosynthetic activity ("revegetating") and more mature forest ("forest"), forest roads differ depending on their surface cover in the spectral signatures captured by the LANDSAT sensor (Bourbier *et al.* 2013; de Wasseige & Defourny 2004). This difference is most pronounced between the reflective bands 3 (red) and 4 (near infrared, NIR) as band 4 is the only one that captures wavelengths where vegetation has a higher reflectance than soil (Richards 2012). The short wave infrared

(SWIR) bands 5 and 7 proved to be less useful in differentiating bare soil and vegetation cover and were only used for corroboration (Figure 2.2).

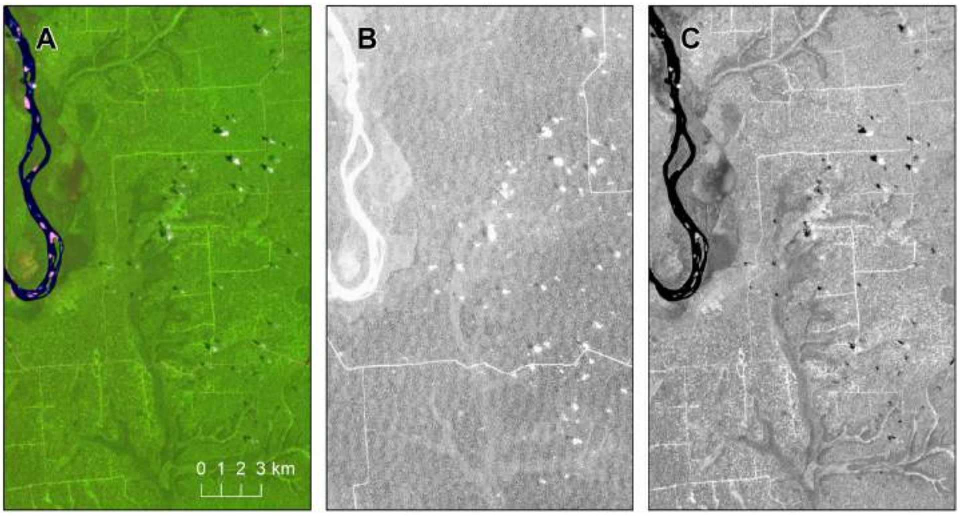

Figure 2.2 – (A) Combination of LANDSAT bands 5, 4, 3 (short wave infrared, near infrared and red channels), (B) band 3 (red channel) and (C) band 4 (near infrared channel) of an identical detailed view from LANDSAT 7 ETM+, dated 15 February 2003. Band 3 is sensitive to bare soil, all roads visible here are classified as "open" roads. Band 4 is sensitive to photosynthetic activity, all roads that are not visible on band 3 but are visible on band 4 are classified as "revegetating" roads. Image contrast enhancement is based on histogram transformation of local standard deviation.

The detection of linear features that are thinner than the pixel size of the images depends mostly on the contrast with the surrounding landscape. If this contrast is apparent, even roads of only 5 or 6 m width can become visible (Albertz & Tauch 1994). In the case of logging roads in the study area, the actual width of the forest clearing for a road is around 20 m (distance between the nearest old growth trees on the two sides of the road, Chapter 3). This results from the common practice of clearing trees to allow the road surface to dry after rain, which is carried out on each side for a distance at least equal to the width of the roadway (Sessions 2007). Visibility of the images was enhanced for the human eye through histogram stretching and equalization (Albertz & Tauch 1994). We manually delineated road segments (henceforth referred to as ‘roads’), each defined by the coordinates of two vertices (a vertex occurs at any change of direction). Through the overlay of several images in each four-year interval, continuous absence of data caused by the scan line corrector problem (SLC-off, Chen *et al.* 2011) since 2003 could be eliminated. Digitization scale was between 1:50 000 and 1:80 000.

The shapefiles of the seven intervals were overlayed in ArcGIS, using the

"Spatial Join" tool, until each road carried the temporal information about its evolution from interval to interval. This information showed in which interval a road was first observed as open. For roads showing a change in classification in subsequent images this would normally be followed by the revegetating phase until the road finally "disappeared", i.e. it was no longer distinguishable from adjacent forest. In very open forest types and highly degraded forests the contrast between revegetating roads and the forest could not be relied on as a criterion for detection. We therefore excluded all roads from the analysis that were only detectable in the open state (i.e. with bare soil) but subsequently (i.e. once covered with vegetation) disappeared from the images without being detectable as revegetating. This was the case in 6% of all road segments. We also differentiated where roads have been re-opened, i.e. the reverse order (transition of revegetating or disappeared roads back to open) was observed. In cases where the re-opened state was again followed by the revegetating state, this was marked accordingly (Figure 2.3).

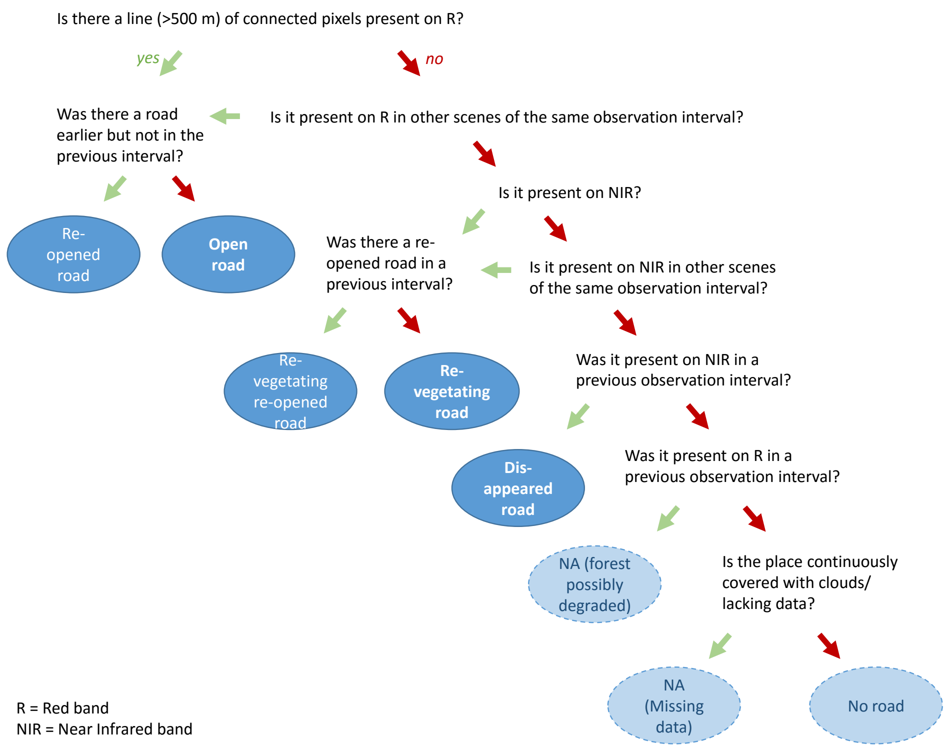

Figure 2.3 – Decision tree for the classification of road segments based on the red and near infrared reflective bands, including potential sources of error.

2.2.3 Accuracy assessment

Given the fact that no systematic assessment of logging activities in the study region exists, we used a combined approach to validate our maps, based on other existing GIS data, high resolution satellite images and field data. We determined how much information each image of the same scene in the same observation interval added. This was done by calculating the proportion of the final data that was based on each of the available images that we had added in the iterative process of road digitization. We then compared the length of our road network with maps of roads (both public roads and those built for logging operations) published by WRI (WRI & MDDEFE 2012; WRI & MEFCP 2010; WRI & MINFOF 2012). These WRI road maps were based on a combination of information from logging companies with satellite images for the year 2008 but it is not clear what time period the information spans over. As a conservative estimate we used all roads that we detected before 2005 to compare with the reference data. We additionally compared the length of our roads with those visible on four SPOT5 images (10-m resolution) from the year 2008, covering 27% of the center of our study area.

We carried out forest inventories in the South-East of Cameroon in February and March 2014, where we set up 76 plots of $5 \times 5\,m^2$ on roads classified on recent LANDSAT 8 images into the different states (open, revegetating, undetectable). With the help of four experienced local forest surveyors we counted all trees ($>$ 1 cm DBH) and identified them wherever possible to the species level. In addition, we estimated the ground cover of the dominant herbaceous genus *Aframomum* (Zingiberaceae). Based on hemispherical photographs taken in each plot, we calculated the gap fraction in the canopy on a 180°half globe over the road using the CanEye software (http://www6.paca.inra.fr/can-eye). We also measured the width of the actual or former road (delimited by the banks of soil accumulated on both sides during road construction) and of the adjacent forest clearing (delimited by the presence of old-growth trees).

2.2.4 Environmental and human infrastructure factors

A homogenized geological map (Fayolle *et al.* 2012) based on three national maps (Boulvert 1996; Gazel 1956; Orstom 1963) was used to identify areas of contrasting “substrate fertility”. Geological types were characterized analogous to Gourlet-Fleury *et al.* (2011). Sandstone and ironstone-capped plateaux and terraces provide a base for nutrient-poor substrates, and alluviums for intermediate substrates. All the other geological formations, sedimentary rocks (tillite, carbonate), acid metamorphic rocks (schist and gneiss), acid igneous rock (granite), basic rocks (dolerite and amphibolite-facies), and mixtures of metamorphic and sedimentary quartzite-sandstone rocks (quartzite), were considered to provide a base for nutrient-rich substrates. This simplified approach allowed us to assign each position in the study area to one of the three substrate fertility classes "poor" (27% of the study area), "intermediate" (30%) or "rich" (43%). We were unable to systematically assess these geological maps, given the lack of other available data. As an approximation (though aware of the substantial differences in the information reported), we used the recent soil map of Africa (Dewitte *et al.* 2013) as a general reference to identify the main soil types in the region. We roughly grouped the soil types by their nutrient richness for comparison with our classification based on geological substrates. We used Arenosols as the reference for poor soils, Ferralsols and Gleysols for intermediate soils and Plinthosols, Alisols, Fluvisols and Nitisols for rich soils (Jones *et al.* 2013). In a GIS overlay analysis we calculated the area where these three soil classes matched those based on the regional geological map.

Altitude was obtained from the Shuttle Radar Topography Mission (Zyl 2001) with a resolution of 90 m. This dataset also enabled calculation of slope as the ratio between the length of each road and the altitudinal difference between its start and end points. Mean annual rainfall was obtained from the "worldclim" dataset (Hijmans *et al.* 2005). The distance to nearest settlement was generated as a variable in ArcGIS by calculating Euclidian distance using the "NEAR"-tool. Due to the lack of recent official maps, positions of towns were obtained from the OpenStreetMap project (http://www.openstreetmap.org), completed and corrected through comparison with older population data but also through visual interpretation of LANDSAT imagery from different years. We identified those settlements that have timber landing sites next to a river or a major road as an indicator that they are a timber transport hub.

2.2.5 Statistical modeling

We compared the field data (tree density, species richness, herbaceous vegetation, canopy cover, road width) amongst the three different satellite-image derived road categories with a Kruskal-Wallis rank sum test and a post-hoc test using pairwise Mann-Whitney tests with Bonferroni correction. A survival analysis was used to analyze time-to-event data (Kleinbaum 2012). While this event is conventionally the death of an individual in a medical study, the applicability of this analysis for land-use-change data has been demonstrated (An & Brown 2008). A key analytical problem in survival analysis is the fact that the time until an event occurs is not known for all samples, mostly because the study has ended early. The last observation time before the event has occurred, which is called censoring time, provides some information (Kleinbaum 2012). In the present study the response variable is the "survival" (i.e. persistence) of each road type (open or revegetating) until a "death"-event occurred, i.e. a change in classification from one interval to the next. We did two separate analyses, one for open roads that changed to the revegetating state and another for revegetating roads that disappeared. Data were marked in the analysis as "right censored" if a road did not change in its state until the final observation interval (2010-2013). To avoid confounding related to differences in timing of the logging history, all roads that already existed in the first observation interval (1986-1989) were excluded from the analysis. This allowed us to identify clearly the time interval in which each road originated in its respective state (initial creation as an open road, or conversion to a revegetating road after abandonment from use) from 1990 onwards.

Persistence for roads was calculated based on Kaplan-Meier survival distributions. These are non-parametric discrete stepped survivorship curves, adding information as each event occurs (Crawley 2005). They are frequently used for descriptive statistics of survival data. Means of these curves are restricted due to the fact that the time when an event happens is not known for all observations and the expected end date is projected. We therefore state medians with 95% confidence intervals whenever applicable. We used the persistence of revegetating roads as the response variable in a Cox proportional hazard model, which provides a robust multivariate regression analysis for survival data. Being semi-parametric, it does not require any assumption about the distribution of survival times. It takes into account survival time and censoring, considering different starting times for a sample to enter the study (Kleinbaum 2012), and is particularly applicable for coarse geospatial time-series data (An & Brown 2008). For factorial variables the reference level was set to the most abundant factor. Information about the relative importance of a variable for the model fit was based on the hazard ratio, generated through exponentiation of the specific regression coefficient (Liu 2012). The closer the hazard ratio gets to 1 the lower is the indicated effect of a variable on the model. As a formal model selection method to identify which of the tested explanatory variables made an important distinct contribution to variation in the response variables we stepwise selected explanatory variables, based on the best model fit, indicated by the Akaike Information Criterion (AIC, Burnham & Anderson 2002).

All statistical analyses were exclusively based on dead-end (i.e. terminal branch) road segments, to make sure that exclusively secondary roads of the same hierarchical level were included, each treated as one sample (Figure 2.4). Only the accuracy assessment with other sources of data (high resolution images, existing road maps) was based on the total length of roads.

All statistical analyses were carried out using R statistical software (R Core Team 2014), applying the packages "maptools" (Bivand & Lewin-Koh 2014) and "survival" (Therneau 2014).

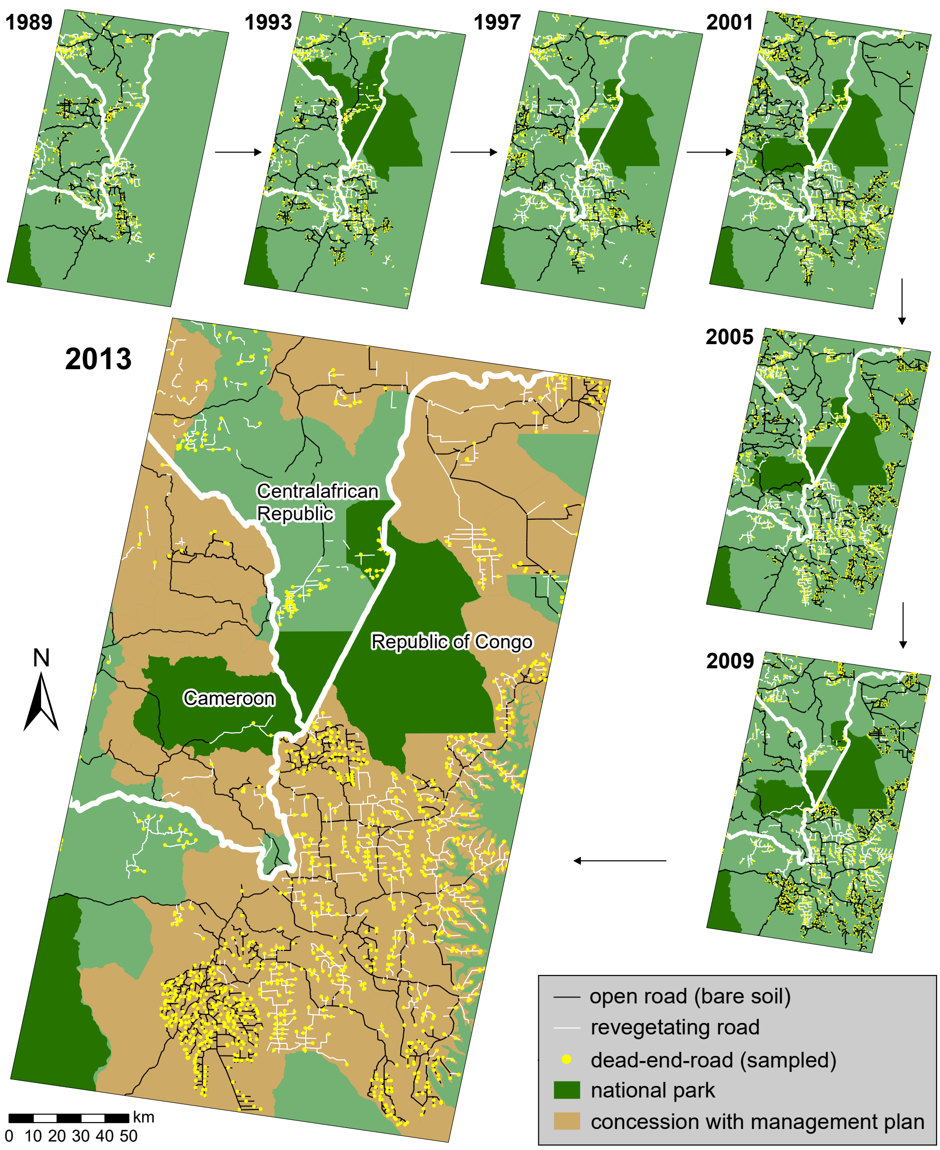

Figure 2.4 – Maps of the logging road network at the end of each four-year observation interval. Open roads (with bare soil) are shown in black, revegetating roads in white; country borders are bold white; national parks have a dark green shading, areas with approved management plans have a brown shading. To make sure that only secondary road segments were included in the analyses, exclusively dead end roads (terminal branches) were sampled (marked with a small yellow dot).

2.3 Results

2.3.1 Accuracy assessment

For most of the observation intervals we had more than three images with low cloud cover available. On average, the first three images contributed 90% of all detected road segments, while additional images only added minor information to the overall map (Figure 2.5). We expect uncertainties due to absence of data, mainly in the two observation intervals between 1990 and 1997, when less than three useful images were available.

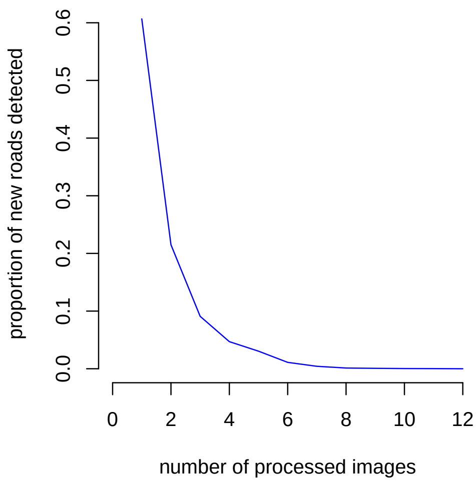

Figure 2.5 – Contribution of each image that was added iteratively to the number of detected road segments on average per observation interval.

The total length of all detected roads was 12% greater on the SPOT images from 2008 than on our LANDSAT based observations in the interval 2006-2009. However, only 5% of the length of all detectable roads on SPOT had not been detected on LANDSAT images in previous observation intervals. This indicates that the differences in resolution between the satellite sensors have a stronger influence on detection of road persistence than on the detection of presence/absence of roads. It also indicates the importance of our analyses being based on data from the same (LANDSAT) sensor throughout. The length of all roads that we detected before 2005 equaled 91% of the road length in the study area in the WRI datasets. The regional geological map used in our analyses had a spatial correlation of 66% with the Dewitte *et al.* (2013) soil map.

There were significant differences amongst the three road classes in terms of total tree density (Kruskal Wallis $\chi^2 = 28.55$, $P < 0.001$) and woody species richness ($\chi^2 = 29.8$, $P < 0.001$). While almost completely absent on open roads, tree density and species richness were also significantly lower on revegetating than on undetectable roads (Figure 2.6). Also, the dominance of the herbaceous genus *Aframomum* was significantly different amongst road classes ($\chi^2 = 19.87$, $P < 0.001$) being highest on revegetating roads, which explains the high photosynthetic activity that their detection on the LANDSAT images was based on. Though gap fraction was higher over open roads, its difference amongst road categories was not significant, indicating that major changes amongst the three categories detected through remote sensing do not result from closure of the upper canopy by in-growth of the crowns of adjacent trees but from succession of vegetation rooted on the road itself. Both road and clearing width did not differ significantly amongst the three road classes, indicating relatively constant road building practice over time and space (Figure 2.6).

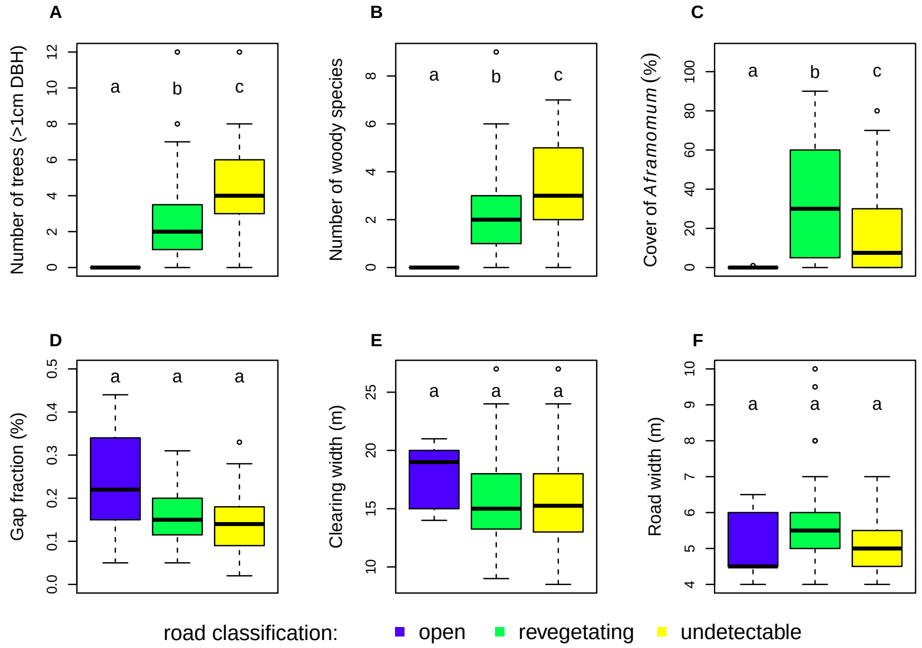

Figure 2.6 – Boxplots for field measurements carried out in February and March 2014 in 5 × 5 m plots on roads detected from LANDSAT 8 OLI images (dated 27 January 2014, 8 March 2014 and 31 March 2014) in the three different states open (blue), revegetating (green) and undetectable (yellow). Variables are (A) tree density, (B) number of woody species, (C) cover of dominant herbs from the genus Aframomum, (D) gap fraction on hemispherical photographs, (E) clearing width and (F) road width. Small letters indicate significant differences between the categories based on the Kruskal-Wallis rank sum test with a Bonferroni corrected pairwise Mann-Whitney-U test for post-hoc comparison.

2.3.2 Modelling of road persistence

There were large changes in the spatial distribution and relative density of the open and revegetating road-types between the seven observation intervals (Figure 2.4). Eighty six per cent of all roads in the study area were observed to be inside logging concessions. Of these, only 3% were in concessions that did not have a management plan at the end of the study (the percentage of the total concession area without a management plan was 8%).

The rate of persistence of open roads was generally low: none of the open roads present before 1997 had survived (persisted) until the last observation interval, 2010-2013, and only 2% of the open roads first observed during 1998-2005 had survived (Table 2.2). 61.24% of open roads first observed in 2006-2009 persisted in this category in the subsequent 2010-2013 interval. The rate of persistence of revegetating roads was greater, with 47.22% of the revegetating roads present in 1990-1993 surviving until 2010-2013 (Table 2.2). The rate of persistence of revegetating roads first observed in each subsequent time interval then increased continuously, which implies that there were no major changes in the survival time (i.e. lifespan) of revegetating roads over the study period (Table 2.2). Six percent of all roads have been observed as re-opened, of which 54% could subsequently be observed in the revegetating state. Re-opened roads showed similar patterns in terms of persistence as those observed for the first time, with a lower probability of surviving until the 2010-2013 interval for those re-opened in 2006-2009 (33.33%, Table 2.2).

The Kaplan Meier median persistence of roads in the open category was 4 (4 - 4) (median with range of 95% confidence interval, CI, in parentheses) years, whereas median persistence of roads in the revegetating category was 20 years (CI not applicable, Table 2.3). Mean persistence of open roads showed very little variation with substrate: 4.15 ± 0.14 (mean $\pm$ SE) years on rich substrates and 4.23 ± 0.22 on poor substrates. In contrast, revegetating roads showed a 4.6-year longer persistence on poor substrates (21.30 ± 0.32) than on rich substrates (16.70 ± 1.18) (Table 2.3). Re-opened roads showed a median persistence of 8 (4 - 12 CI) years, which was markedly longer on poor substrates (16 years, CI not applicable) although this was based on a low number of observations. Re-opened roads persisted for 12 (8 - 12 CI) years in the revegetating state.

Given that most open roads persisted for a shorter time than the four-year observation interval, the spatial variation in persistence of roads in this open state was too low to be used convincingly as a response variable in a Cox proportional hazard model. We also observed large differences between the three substrate fertility classes in their distributions along the gradients of altitude and distance to settlement: the distributions for poor and rich substrates were generally similar to each other, with those of intermediate

Table 2.2 – Number of secondary logging road segments observed for the first time during each observation interval and the probability for these road segments to survive in the same state until the last observation interval (2010-2013).

Interval of first observation	New roads observed	Roads disappeared†	Roads survived‡	Survival (%)
Open roads				
1990-1993	70	70	0	0
1994-1997	87	87	0	0
1998-2001	242	241	1	0.41
2002-2005	189	186	3	1.59
2006-2009	178	69	109	61.24
2010-2013	324	0	324	100
Revegetating roads				
1990-1993	144	76	68	47.22
1994-1997	156	74	82	52.56
1998-2001	138	47	91	65.94
2002-2005	78	22	56	71.79
2006-2009	151	41	110	72.85
2010-2013	169	0	169	100
Re-opened roads				
1990-1993	0	0	0	0
1994-1997	14	14	0	0
1998-2001	24	24	0	0
2002-2005	24	24	0	0
2006-2009	12	8	4	33.33
2010-2013	24	0	24	100
Revegetating re-opened roads				
1990-1993	0	0	0	0
1994-1997	2	2	0	0
1998-2001	5	5	0	0
2002-2005	15	13	2	13.33
2006-2009	15	4	11	73.33
2010-2013	16	0	16	100

Note: The results are separated between road categories in two states (classified as open or revegetating) that each are again separated based on whether they were observed for the first time (top two sections of table) or have been re-opened after the previous road had disappeared (lower two sections of table).
† Road segments that could no longer be classified to be in the same state in the images of the final observation interval.
‡ Road segments observed in the same state until and including the final observation interval.

substrates being more distinct for both gradients. Therefore we excluded the intermediate substrates from the subsequent statistical analyses.

Table 2.3 – Kaplan-Meier survival time (persistence) measured in four-year-intervals for secondary logging road segments, differentiated by road state and substrate nutrient content type based on classification of geology.

				survival time (years)	
Road state	Substrate type	Observations	Events†	Mean ± SE ‡	Median (95% CI) §
Open	All	1090	653	4.2 ± 0.11	4 (4-4)
	Rich	309	165	4.15 ± 0.14	4 (4-4)
	Intermediate	507	392	4.25 ± 0.25	4 (4-4)
	Poor	274	96	4.23 ± 0.22	4 (4-4)
Revegetating	All	836	260	18.69 ± 0.44	20 (NA)
	Rich	230	100	16.7 ± 1.18	16 (16-20)
	Intermediate	439	100	18.4 ± 0.71	NA
	Poor	167	60	21.3 ± 0.32	NA
Re-opened	All	98	70	7.2 ± 0.93	8 (4-12)
	Rich	61	36	7.23 ± 0.86	8 (4-12)
	Intermediate	25	24	4 ± 0	4 (NA)
	Poor	12	10	15.27 ± 0.87	16 (NA)
Revegetating re-opened	All	53	24	11.6 ± 0.95	12 (8-12)
	Rich	24	19	11.4 ± 0.87	12 (8-12)
	Intermediate	22	2	15.8 ± 2.68	14 (NA)
	Poor	7	3	12 ± 0	12 (NA)

Note: Results are separated as described in the notes of Table 2.2.
† Shift from the open to the revegetating state or from the revegetating state to disappearance.
‡ Mean values (with standard errors) are restricted due to skewedness of the data.
§ Median values are shown with the range of the 95% confidence intervals, wherever applicable. NA denotes cases where calculation was not applicable due to a low proportion of observations with events occurring.

The selected best Cox proportional hazard model for revegetating roads included three explanatory variables: geological substrate, altitude and distance to settlement (Table 2.4). Slope and rainfall were excluded during variable selection. Road persistence was significantly longer on poor compared with rich substrates ($P < 0.001$) and road persistence was shorter with higher altitude ($P < 0.001$). The distance to nearest settlement was associated with increasing persistence of revegetating roads ($P = 0.005$).

2.4 Discussion

The persistence of scars in forest cover resulting from secondary logging roads is limited. These roads are temporary elements in the landscape that vary in the timespan of their threat to the forest ecosystem. Open roads are considered worst for environmental damage and poor delivery of ecosys-

Table 2.4 – Results of a Cox Proportional Hazard survival analysis for secondary logging road segments in the revegetating state.

Explanatory variable	Parameter estimate†	Hazard ratio ± SE	*P* value
Poor substrate‡	-0.622	0.537 ± 0.168	<0.001***
Altitude	0.362	1.436 ± 0.068	<0.001***
Distance to nearest settlement	-0.446	0.640 ± 0.160	0.005**

Notes: n = 397, number of events = 160, re-opened road segments and intermediate substrates were excluded from the analysis.
† Positive parameter estimate values indicate higher hazard for a road to disappear, i.e. shorter survival times (decrease in persistence); negative values vice versa.
‡ Substrate nutrient content type based on classification of geology. For this factorial variable the reference level was set to the most abundant factor (rich substrate).

tem services (Laurance & Useche 2009; Wilkie *et al.* 2000), but open roads mostly persisted for less than four years. This indicates that spontaneous revegetation follows road abandonment without major delays. Revegetating roads persisted in that state more than four times as long as open roads but they are assumed to have already recovered some of their capacity to deliver ecosystem services and to be on a trajectory towards full forest recovery. However, we found contrasts in the duration of re-vegetation processes that indicate strong site-specific differences in the rate of forest recovery on roads. As already hypothesized by Gourlet-Fleury *et al.* (2011) for logged forest, the recovery of forest cover through regeneration on roads was delayed on resource-poor substrates. These findings highlight the importance of considering site conditions determined by substrate fertility for the planning of logging operations.

Recovery of vegetation cover on logging roads has occurred continuously over the past 28 years: the earlier a road was abandoned, the lower is the probability that it is still detectable as a road today. The observed sequence of road-states from open through revegetating to undetectable, represents a successional trajectory in which bare soils first become colonized by dominant herbaceous species that are then overgrown by an increasing density of trees, with increasing species diversity. Previously, abandoned logging roads have been identified as long-lasting corridors, characterized by uniform floristic patterns (Guariguata & Dupuy 1997). We found evidence that the timespan that these corridors are detectable depends on site factors. By limiting our analyses to dead-end secondary logging roads we greatly reduced the potential for differences in road-use frequency to influence the results. This allows us to make a powerful use of the novel approach of analyzing roads as human infrastructure to determine the major factors limiting the rate of forest recovery after logging through natural regeneration processes. We do not have any further information about differences in road construction but given the remoteness of the whole study area combined with our own field observations, we are confident that all these dead-end roads were built in a similar way, without any surfacing operations having taken place.

We found forest recovery to be slower on resource-poor substrates. Slow regeneration of tropical forests on soils of poor quality is a well-known general issue (Crk *et al.* 2009; Finegan 1996). However, this has only recently arisen as a concern in the Congo Basin (Gourlet-Fleury *et al.* 2011) where it has not yet been taken into account in forest management practices (N. Bayol *personal communication*). Large parts of the southern CAR and the northern Republic of Congo are characterized by "Carnot" sandstone, producing resource-poor soils associated with dense, slow-growing forest types (Figure 2.1, Fayolle *et al.* 2012; Gond *et al.* 2013). Here, a new logging frontier has been opened only since 2000 (Figure 2.4, Laporte *et al.* 2007). This logging boom in the far north of Republic of Congo had its peak in about 2004, so it is not yet possible to draw conclusions about persistence of most of the relatively new roads in this area. However, our results lead to concern that they may revegetate as slowly as those roads created earlier on similar substrates in CAR.

Our results show that secondary logging roads persisted for a shorter time at higher altitudes. However, neither topographic slope nor rainfall improved the statistical model. Given that the available topographic and climatic data are very coarse, it is possible that small-scale variations in either of the variables do influence natural regeneration on roads. However, the effect of altitude on detectability of roads might also be linked with forest structure which is likely to differ with altitude in the study area. Revegetating roads persisted in this state for a longer time when they were located further away from settlements. Given the consistency in the management of forest concessions, the duration of use of logging roads is similarly short throughout the forest of the study area. Therefore the Von Thünen model, where forest degradation decreases with rising transportation costs to the market (Angelsen 2007; Chomitz & Gray 1996), does not seem to apply to the rate of forest recovery on these roads. Instead, our findings could be a result of the variation in logging history across the study area which may be linked with distance to settlement. The forest landscapes on resource-rich soils in the western part of the study area that have a longer history of disturbance and higher settlement density (and thus shorter average distance to settlement) are likely to have a greater abundance of fast-growing, light-demanding tree species

(Sheil & Burslem 2003). The abundance of these species in the forest might accelerate the process of forest regrowth on abandoned roads, reducing the contrast between road and forest faster than in less disturbed forest landscapes. In contrast, in the east of the study area (northern Republic of

Congo) there is a shorter logging history and lower settlement density (and thus higher average distance to settlement). In contrast to other places where the proximity to less disturbed forests promotes faster recovery after disturbance (Chazdon 2003), here the rate of detected forest recovery on roads (based on the contrast with the surrounding forest) may be slower because of a lower density of fast-growing pioneer species in the surrounding forest (*personal observations*).

Given the longer persistence of logging roads on resource-poor substrates, careful road planning as part of sustainable forest management needs to take such local site conditions into account. Reduced impact logging (RIL) is usually associated with lower densities of harvested trees (Medjibe & Putz 2012) to enable sufficient regeneration of timber species. However, if this results in an extensification of logging over a larger area requiring an expansion of the road network into vulnerable sites, there may be no net gain (Gullison & Hardner 1993; Schneider 1995). Instead, a reduction of total harvest area by concentrating logging operations in areas identified as more productive combined with silvicultural intensification (Fredericksen & Putz 2003) needs to be considered for the Congo Basin area. This would allow less productive areas to be protected for conservation without, or with a reduction in, timber harvesting. This "land sparing" over "land sharing" strategy has been advocated for logging activities by Edwards *et al.* (2014a). A way to achieve sustainable intensification in more productive areas in the Congo Basin is the diversification of harvested species (Karsenty & Gourlet-Fleury 2006) and the implementation of post-logging silviculture (Gourlet-Fleury *et al.* 2013).

Further research, taking into account the spatial distribution of the road network, is needed to determine whether or not existing roads should be re-opened for subsequent timber harvests and how such a more intensively used but overall smaller road network would affect the forest landscape and its ecosystem function. During the study period, we detected very few re-opened roads, although this is considered a common practice in managed concessions during subsequent cycles of logging operations, usually as the lowest cost option (N. Bayol *personal communication*). According to Karsenty & Gourlet-Fleury (2006), the very first cut of selective logging is mainly focused on the "cream", i.e. the most valuable, internationally traded species. Only if the expected timber yield justifies the high transport costs would this be followed by a second cut, e.g. because a market for less well known species has developed (Karsenty & Gourlet-Fleury 2006). Although the duration of the study period and the number of samples are both low, our results do already indicate that re-opened roads persisted for longer in the open state but shorter in the revegetating state, compared with new roads. Both might be a sign of an increased level of forest degradation: initially it takes longer until vegetation cover is established (e.g. due to a higher level of soil compaction), then the recovering vegetation on the road soon becomes very similar to the surrounding forest that has been degraded to a greater extent through repeated logging.

Our analyses show a very dynamic secondary logging road network that appears only for a relatively short time. It is therefore difficult to use logging roads in the Congo Basin as static indicators of forest degradation and fragmentation. Recent studies (Bell *et al.* 2012; Brandt *et al.* 2014) have used road networks in the Congo Basin to quantify the extent of logging activities in relation to forest management and forest concession ownership. Taking road persistence into account could strongly enhance the accuracy of such analyses. This should be accompanied by further field-based vegetation inventories to quantify species composition, rate of recovery of biomass and forest stature on and adjacent to logging roads in relation to the time of their abandonment. The highly dynamic nature of forest roads (with a low level of persistence) appears much more complex than is assumed in standard measures of habitat patch fragmentation. This calls for the development of new tools to quantify the fragmentation impact of non-permanent roads in forest landscapes.

2.5 Conclusions

We have presented the assessment of temporal dynamics in logging road networks as a tool to characterize differences in recovery of forest vegetation in areas of contrasting environment and with different disturbance histories. Our results suggested that substrate-related site factors are slowing down the progress of succession on logging roads. This informs better planning of forest management to accelerate recovery of forest on roads. The influence of substrate fertility on the rate of forest regeneration needs to be included in management of sustainable logging practices. In areas of resource-poor substrate, where roads recover more slowly, there should be a presumption against construction of new roads because the capacity of these areas to sustain repeated cycles of logging without degradation of the forest landscape is low.

Chapter 3

How persistent are the impacts of logging roads on Central African forest vegetation?

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Abstract

1. Logging roads can trigger tropical forest degradation by reducing the integrity of the ecosystem and providing access for encroachment. Therefore, road management is crucial in reconciling selective logging and biodiversity conservation. Most logging roads are abandoned after timber harvesting; however, little is known about their long-term impacts on forest vegetation and accessibility, especially in Central Africa.
2. In 11 logging concessions in the Congo Basin we field-sampled a chronosequence of roads that, judging from satellite images, had been abandoned between 1985 and 2015. We assessed recovery of timber resources, tree diversity and above-ground biomass in three zones: the road track, the road edge (where forest had been cleared during road construction) and the adjacent logged forest.
3. The density of commercial timber species < 15 cm DBH was almost three times higher in the road track (321 individuals ha^{-1}) and edge (267) than in the logged adjacent forest (97). Over time, tree

species diversity converged to a comparable level between roads and adjacent forests, along with an increase in canopy closure.

4. The average width of forest clearing for road construction was 20 m, covering a total 0.76% of the forest area inside concessions. After 15 years following abandonment, road tracks had recovered 24 Mg ha^{-1} of above-ground woody biomass, which was 6% of that in the adjacent forest, while road edges had accumulated 167 Mg ha^{-1} (42%). Ten years after abandonment, roads were no longer penetrable by poachers on motorcycles. An exotic herb species was fully replaced by dominant Marantaceae that have even higher abundance in the adjacent forest.
5. *Synthesis and applications.* Our evidence of vegetation recovery suggests that logging roads are mostly transient elements in forest landscapes. However, given the slow recovery of biomass on abandoned road tracks, we advocate both reducing the width of forest clearing for road construction and reopening old logging roads for future harvests, rather than building new roads in intact forests. Road edges seem suitable for post-logging silviculture which needs to be assisted by removing dominant herbs during the early years after abandonment while the road track is still accessible.

3.1 Introduction

Large parts of the world's humid tropical forests are selectively logged (Asner *et al.* 2009) and there is an urgent need to reconcile this method of exploitation with biodiversity conservation (Edwards *et al.* 2014b). A key element in reducing selective logging impacts is management of the extensive road networks built into the forest (Mason & Putz 2001). Road construction requires full clearance of narrow linear sections of the forest area, with far reaching consequences for the forest ecosystem though fragmentation, desiccation and spread of invasive species (Laurance *et al.* 2009). Despite bringing potential benefits to local people, frontier roads in remote forests are therefore mostly considered to threaten biodiversity conservation especially due to their widespread use by bushmeat hunters (Wilkie *et al.* 2000).

On a global-scale road map, major parts of Central Africa have been classified as a priority road-free area due to their species richness and high carbon stocks (Laurance *et al.* 2014). However, logging road networks in the Congo Basin have been expanded greatly over the last 20 years (Laporte *et al.* 2007) to gain access for selective logging of a few, high-value timber species, notably *Entandrophragma cylindricum* (Sapelli) (Karsenty & Gourlet-Fleury 2006). Up to 53% of the biomass of this valuable species has been harvested in one concession (Gideon Neba *et al.* 2014), likely depleting the available timber stock (Hall *et al.* 2003). Forest clearing for road building in selective logging operations also causes carbon emissions

(Putz *et al.* 2012), but the magnitude of this contribution and the extent to which the carbon is recaptured during subsequent vegetation recovery remain unclear.

Not all timber extraction roads have the same impact. Secondary logging roads, only used to transport logs from where they were cut to a main road, are usually abandoned immediately afterwards (Malcolm & Ray 2000). On LANDSAT images they are detectable with bare soil for less than four years and covered with vegetation for 20 years before they are no longer distinguishable from surrounding forest (Kleinschroth *et al.* 2015). Only 12% of roads in forest concessions observed over the last 15 years have been permanently open (Kleinschroth *et al.* 2016a). Abandoned logging roads have been characterized as long-lasting and relatively uniform floristically and structurally altered long corridors that may have particular ecological functions in selectively logged forests (Guariguata & Dupuy 1997). Especially in areas where high volumes of timber are harvested, such as the dipterocarp forests of South-East Asia, reduced levels of regeneration have been reported on abandoned roads and skid trails due to unfavourable soil conditions such as compaction and low nutrient content (Pinard *et al.* 2000; Zang & Ding 2009). In contrast, for regions with low intensity logging regimes in South America, logging roads and strip clearcuts have been associated with enhanced levels of regeneration of light demanding timber species (Fredericksen & Mostacedo 2000; Hartshorn 1989; Nabe-Nielsen *et al.* 2007). Few comparable studies exist for Central Africa; however, Malcolm & Ray (2000) reported reduced sapling densities and tree species richness on and alongside abandoned logging roads compared with unlogged forests. In Central Africa harvesting intensity is generally low (1–2 trees per ha, Karsenty & Gourlet-Fleury 2006). Here, roads are the most costly and destructive components of logging operations (Mason & Putz 2001) and their long-term management is thus crucial for impact reduction.

The existing studies about forest regeneration on abandoned logging roads are mostly based on small sample sizes with limited spatial and temporal coverage. In contrast, we used remote sensing information (Kleinschroth *et al.* 2015) to identify roads abandoned over a continuous chronosequence of dates between 1 and 30 years ago, spanning a large area (25 000 km^2) and different geological substrates. This study investigates the trajectory of vegetation succession and environmental conditions after logging road abandonment to find out how long-lasting are the threats of roads to forest ecosystems due to low recovery rates after logging disturbance and resulting persistence in fragmentation. We assessed recovery in terms of regeneration of commercial timber species, tree species diversity and above-ground woody biomass (AGB) and linked this with soil condition, herb cover and reduced accessibility to poachers. From this evidence we suggest how the resilience of forest landscapes can be incorporated into better road management strategies to enable more sustainable forest exploitation and effective restoration.

3.2 Methods

3.2.1 Study area

The catchment of the Sangha River, a major tributary of the Congo, has been subject to widespread logging activity. In order to cover a broad range of its forests, we selected 11 logging concessions, owned by four different companies (Alpi, OLAM, Rougier, Decolveneaere), in the Eastern province of Cameroon (centred at 3.724 N, 14.616 E) and the Sangha and Likouala provinces of Republic of Congo (centred at 1.855 N, 16.417 E). The total area of all 11 studied concessions is 25 049 km^2 located within a total forest area of ca. 100 000 km^2 (Figure 3.1). The area's logging history is long with some concessions dating back to the 1960's, while in others logging started only after 2000 (Laporte et al. 2007). The forest is mostly semi-deciduous and altitude range is 350–650 m. All 11 concessions are certified by Origine et Légalité des Bois and four of them are certified by the Forest Stewardship Council. All are operating according to a forest management plan that includes the assignment of annual felling areas (assiettes annuelles de coupe, AAC).

3.2.2 Study design

Using a time series of LANDSAT images, we identified a chronosequence of roads abandoned between 1985 and 2015 (Figure 3.1). As all the roads are in dedicated logging concessions, we assumed that they had been built for logging purposes. We defined road abandonment as a state shift from being actively used by cars and trucks to being in the process of revegetation. The years of road use were indicated by the presence of bare soil. Given the differences in spectral properties between bare soil and recovering vegetation the first year when a road was abandoned could be determined based on the difference between the red and near-infrared channels on the LANDSAT images (Kleinschroth *et al.* 2015). For the time before 1997, images were not available in regular intervals and some roads could only be detected after they had already been abandoned. In these cases we assumed that road activity had ceased in the preceding year. The study area is covered by four LANDSAT scenes (P183, RR57-58, P182, RR58-59). We used the whole range of images available on http://glovis.usgs.gov, covering images of LANDSAT 5, 7 and 8 (all 30-m pixel size). Due to differences in image availability and quality, more than 130 images were grouped and processed together in the following intervals: before 1986, 1986–1987, 1988–1989,1990–1993,1994–1997, 1998–1999, 2000–2001, 2002–2003, 2004–2005, 2006–2007, 2008–2009, 2010–2011, 2012–2013, 2014–2015. We corrected the final road

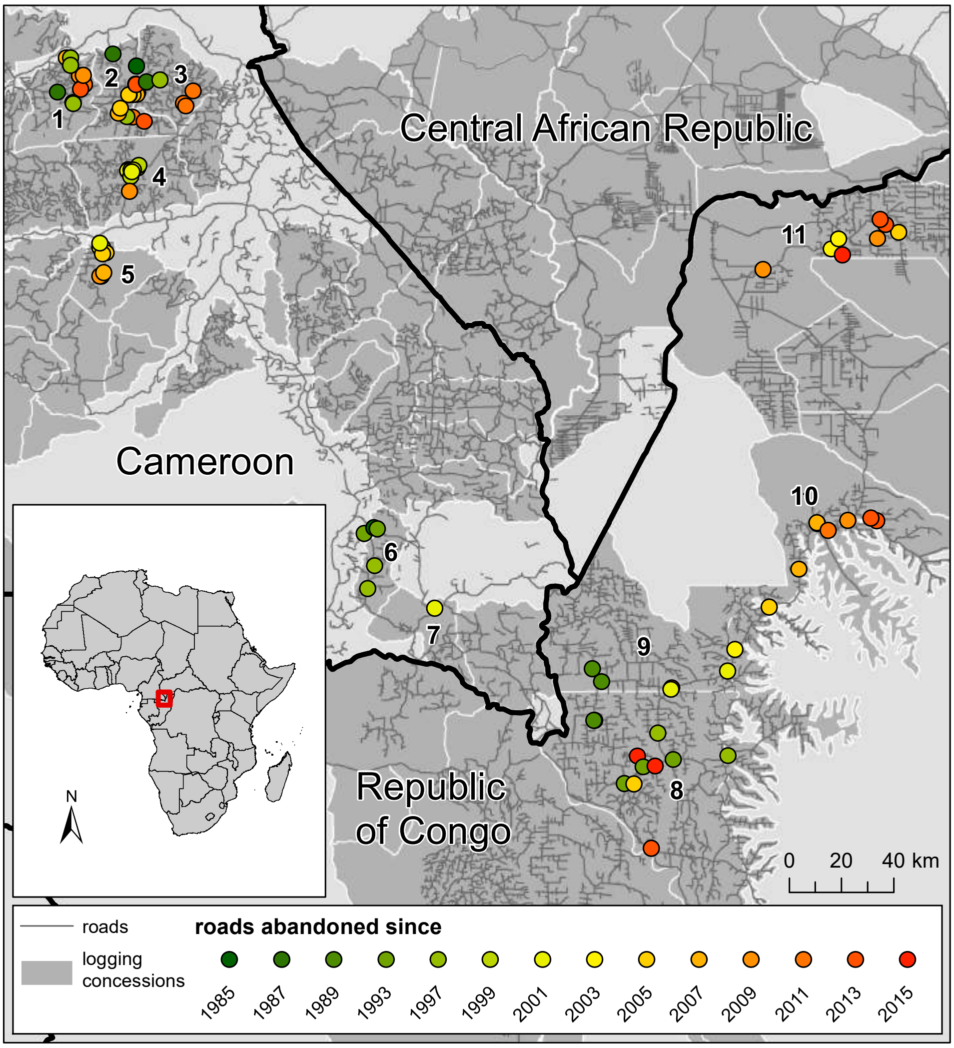

Figure 3.1 – Map of the 86 roads sampled in the study. Colour gradient from green to red depending on time of abandonment based on interpretation of Landsat images. White lines indicate concession boundaries, sampled concessions are consecutively numbered.

map with the WRI forest atlases of Cameroon and Congo that include the AAC felling areas for each year (http://www.wri.org/our-work/project/congo-basin-forest-atlases). The accuracy of the road map was continuously tested while travelling over 2000 km of roads in the study area, using a mobile GIS, comparing the interpretation of recent images with the situation on the ground.

3.2.3 Plot design

On each of a randomized sample of 86 roads, within strata based on year of road abandonment, we laid out two 50-m gradient-directed transects (gradsects, Gillison & Brewer 1985), separated by 50 m and each perpendicular to the opposite side of the abandoned road (Figure 3.2 a). This form of sampling across a steep environmental gradient has been shown to be accurate and more effective than fully random designs and to be useful in regression-type analyses in tropical forests (Parker *et al.* 2011). We adapted the transect design so that each contained three subplots of 5×5 m placed systematically in three parallel zones on a gradient of road-related disturbance (Figure 3.2 b). The road track was characterized by the removal of top soil and sometimes the application of a surface cover of laterite to facilitate traffic (Sessions 2007). It was demarcated by accumulated soil embankments on both sides (Guariguata & Dupuy 1997). In 16% of the plots the road track was less than 5 m wide and so included up to 1 m of the opposite edge. The road edge is the area on both sides of the track that had been cleared of all vegetation to allow the sun to dry the road surface (Sessions 2007). It was characterized by accumulated soil from road building. The adjacent forest was more-or-less old growth but showed occasional signs of selective logging. Slash from vegetation cleared during road construction was found to be removed to the adjacent forest but no systematic piling of slash was apparent. The road track and edge zones were directly adjacent to each other, with the former roadside ditch marking the border. The forest subplot was placed selectively beyond the edge zone at the first position along the transect with no more visible influence from the former road. This was on average 41.7 m away from the road track. The design was fully balanced among the three zones with two triplets of plots per sample site (Figure 3.2 a). The small size of the subplots is adapted to inventorying the early succession stages on the narrow road track and edge and is less suitable for the characterization of mature forest. The third subplot therefore serves more as a coarse reference.

3.2.4 Data collection

Fieldwork took place in February/March 2014 and 2015 when in each subplot we measured diameter at breast height (DBH) and height of each

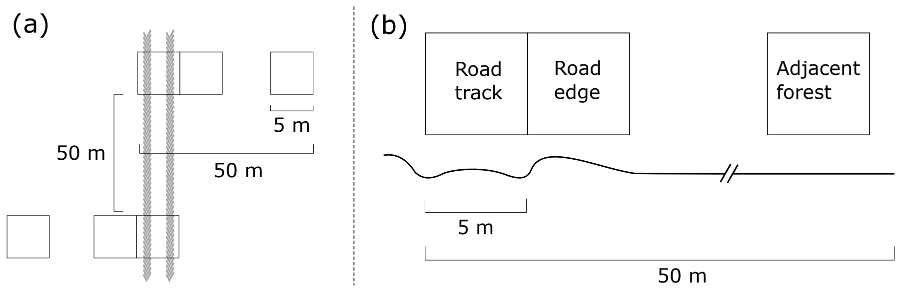

Figure 3.2 – Plot design with the location of subplots (a) in plan-view on and alongside the abandoned road and (b) as a cross-section from the road track into the adjacent forest showing the profile of the soil surface.

stem of all self-standing woody plants $\geq$ 1 cm DBH and $\geq$ 1.3 m high. Only taxa identified with an accepted name in the African Flowering Plants database (http://www.ville-ge.ch/musinfo/bd/cjb/africa/recherche.php) were included in the analyses (excluding 2% of observed individuals). Identification was done by local botanists and forest prospectors. Non-commercial species were analysed at the genus level to minimise the effect of any misidentifications at the species level. For 91% of all individuals we were able to assign a regeneration guild based on the literature (Fayolle *et al.* 2014; Hawthorne 1995).

Tree species of commercial interest (Table S1) were defined based on a list of 35 species targeted for selective logging across the Congo Basin (Ruiz Pérez *et al.* 2006), corrected by an internal list of commercially valuable tree species (CIB, unpublished). To differentiate roughly between recruits and mature trees we divided all individuals between two diameter classes, $\geq$ 1 and $<$ 15 cm and $\geq$ 15 cm DBH This value was determined in a pilot study based on the maximum diameter of timber trees found on road tracks and edges. For tree diversity we used the Shannon-Index on the genus level (Magurran 2004). Above-ground woody biomass was calculated with a pantropical allometric formula (Chave *et al.* 2014):

$$AGB_{est} = 0.0673 \times (\rho D^2 H)^{0.976} \tag{3.1}$$

Where ρ is wood specific gravity, D diameter at breast height and H height. Wood specific gravity was extracted from the DRYAD database (Zanne *et al.* 2009), completed with data from a CIRAD database of wood specific properties (http://tropix.cirad.fr/). Whenever possible we calculated means of wood specific gravity at the genus level, otherwise at the family level. For the 6.9% individuals with no available data, we used subplot-wide means.

The main explanatory variables were those used in the sample stratification, namely time after road abandonment, which we analysed using the chronosequence assumption in a space-for-time substitution (Terborgh *et al.* 1996), and habitat zone (road track, edge, adjacent logged forest). Additionally we measured the clearing width, i.e. the corridor where forest cover had been fully removed during road construction indicated by the absence of mature trees. Other explanatory variables were derived from the measurement of site- and soil-related factors. We assessed canopy closure above a measurement height of 1.3 m using one hemispherical photograph in the centre of each subplot, evaluated with the application HabitApp (Macdonald & Macdonald 2016). This information was corroborated with an independent visual assessment of canopy closure from the centre of each subplot (Jennings *et al.* 1999). Soil compaction was measured as the mean of five random measurements per subplot with a pocket penetrometer (Eijkelkamp, Giesbeek, Netherlands) to determine the penetration resistance of the top soil layers (range 0-5 kg/cm^2, depth 6.35 mm). Each of the 86 road sample sites were classified into three soil fertility classes (rich, intermediate, poor) based on maps of geological substrate as described by Kleinschroth *et al.* (2015). This information was corroborated by soil texture determined by feel-analysis with 90% of rich substrates being characterised by clay loams, a ratio of 1/3 loam and 2/3 sand for intermediate substrates and 100% sand for poor substrates. Where the substrate is poor soil derived from sandstone the forest has mostly only been opened for logging after 2000 (Kleinschroth *et al.* 2015), with the oldest sampled road abandoned 12 years ago (concession 11 in Fig. 1). The thickness of the litter layer was measured as the mean of five random measurements per subplot with a ruler. The dominant herbaceous species (including non-woody climbers) in each subplot were identified and their cover estimated in per cent as a projection on the plot surface. This included mostly species from the Marantaceae family as well as the genus *Aframomum* (Zingiberaceae) and the non-native species *Chromolaena odorata* (Asteraceae). The sampled concessions showed pronounced differences in AGB (Table S1) due to differences in tree density and species composition. Given the limitations of our small plot size we used 395.7 Mg ha^{-1} (Lewis *et al.* 2013) as a reference for mature forests.

We assessed current human access on each of the 86 abandoned road sites based on the presence of different types of path, informed by the local knowledge of field guides and occasional observations of path users. A footpath was characterized by a narrow trampling line, interrupted by rougher sections including climbs due to obstacles such as fallen trees as well as stream crossings with logs as improvised bridges. A motorcycle path was indicated by a continuous line of open soil or disturbed vegetation with bypasses at any obstacle, especially at the junction with a permanently-open access road, where logging companies had usually placed log barriers.

3.2.5 Statistical modelling

We applied data exploration following the protocol of Zuur *et al.* (2010), using Cleveland dotplots to inspect the variables for outliers and pairwise scatterplots to assess collinearity. We strictly avoided collinearity among the covariates. This approach led us to use a fixed set of variables comprised of time after abandonment, clearing width, road-habitat zone and geological substrate for all models. To avoid heteroscedasticity we applied log transformation, combined with adding a constant of 0.01 to all basal area and AGB variables. Due to a high number of plots without observations of commercial species we fitted two different models to explain regeneration of commercial trees: (a) frequency of presence/absence and (b) basal area of only those commercial species ≥ 1 and < 15 cm DBH that were present. Each subplot was treated as a replicate. To avoid pseudo-replication, sites located inside the same felling area (AAC) were assumed to be non-independent. To take account of this nested design we included AACs as random factors in a mixed effects regression model. The 86 roads sampled were distributed over 63 AAC's. We used generalized linear mixed models (GLMM) for presence/absence of commercial species with Bernoulli distribution and linear mixed models (LMM) for the normally distributed variables Shannon diversity index, log-transformed basal area and AGB. There is ongoing debate about the use of p-values in such models (Pinheiro & Bates 2000), therefore we applied a bootstrapping procedure with 100 replications to construct confidence intervals. Only if 0 did not fall within the 95% confidence interval was the variable assumed to be significant (Figure 3.3, Table 3.1). An increase of the bootstrap replications up to 1000 did not produce any difference in the results. We calculated floristic dissimilarity between groups of plots using the incidence-based Jaccard and abundance-based Morisita-Horn indices (Magurran 2004). The Jaccard-index was visualized using Kruskal's non-metric multidimensional scaling (NMDS). To compare the presence of paths with age of road we used non-parametric Kruskal-Wallis tests with Mann-Whitney U statistics (Wilcoxon rank-sum test) as post-hoc tests. All analyses were carried out in R (R Core Team 2014), using the packages "vegan", "lme4" "boot" and "ggplot2".

3.3 Results

3.3.1 Regeneration of commercial species

Of the total number of 173 recorded tree genera we identified 26 species (among 35 potential ones) that have commercial timber value. Their combined density was 321 individuals < 15 cm DBH ha^{-1} in the road track and 267 in the edge zone, compared with 97 trees < 15 cm DBH ha^{-1} in the adjacent forest. There were five individuals ≥ 15 cm DBH ha-1 in the road

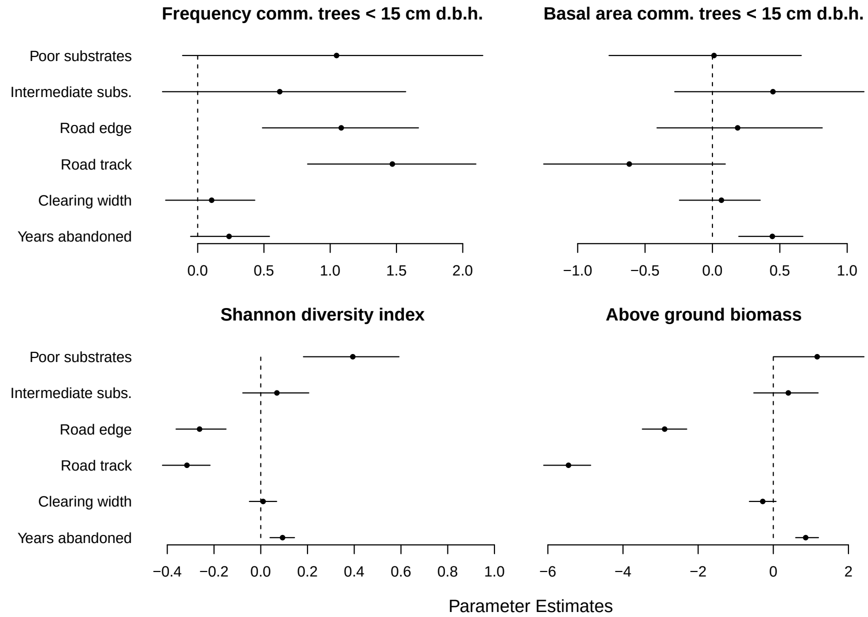

Figure 3.3 – Effects of substrate (poor, intermediate), habitat zone (road track, edge), clearing width and time (years after abandonment) on frequency and basal area of individuals < 15 cm DBH of commercial tree species, Shannon diversity index and above-ground biomass. Effect sizes are results from linear mixed models (for frequency: generalized linear mixed model) with AAC as a random effect, and are presented with 95% CIs; those that do not overlap the dashed vertical line are statistically different from zero. Negative values indicate negative correlations, positive vice-versa.

track, 24 in the edge and 63 in the forest (Supporting table 3.2). The frequency of commercial species' individuals < 15 cm DBH was higher in the road track (45.3% of plots, $P < 0.001$) and in the edge (37.7%, $P < 0.001$) than in the adjacent forest (19.3%, Figures 3.3 and 3.4). The presence-only model for the log-transformed basal area of commercial species' individuals < 15 cm DBH showed no difference between the road habitat zones but a significant positive trend with time after abandonment ($P = 0.001$, Figure 3.8). Road edges abandoned > 15 years ago had the highest basal area of timber species recruits (Mean ± CI: 0.74 ± 0.55 $m^2 ha^{-1}$) followed by the road track (0.54 ± 0.31), both higher than in the adjacent forest (0.16 ± 0.14) due to a decreasing trend over time (Figure 3.4).

3.3.2 Tree diversity

The Shannon diversity index of tree genera for individuals ≥ 1 cm DBH was significantly lower in road track and edge zones (both $P < 0.001$) than in adjacent forest. However, diversity increased significantly over time

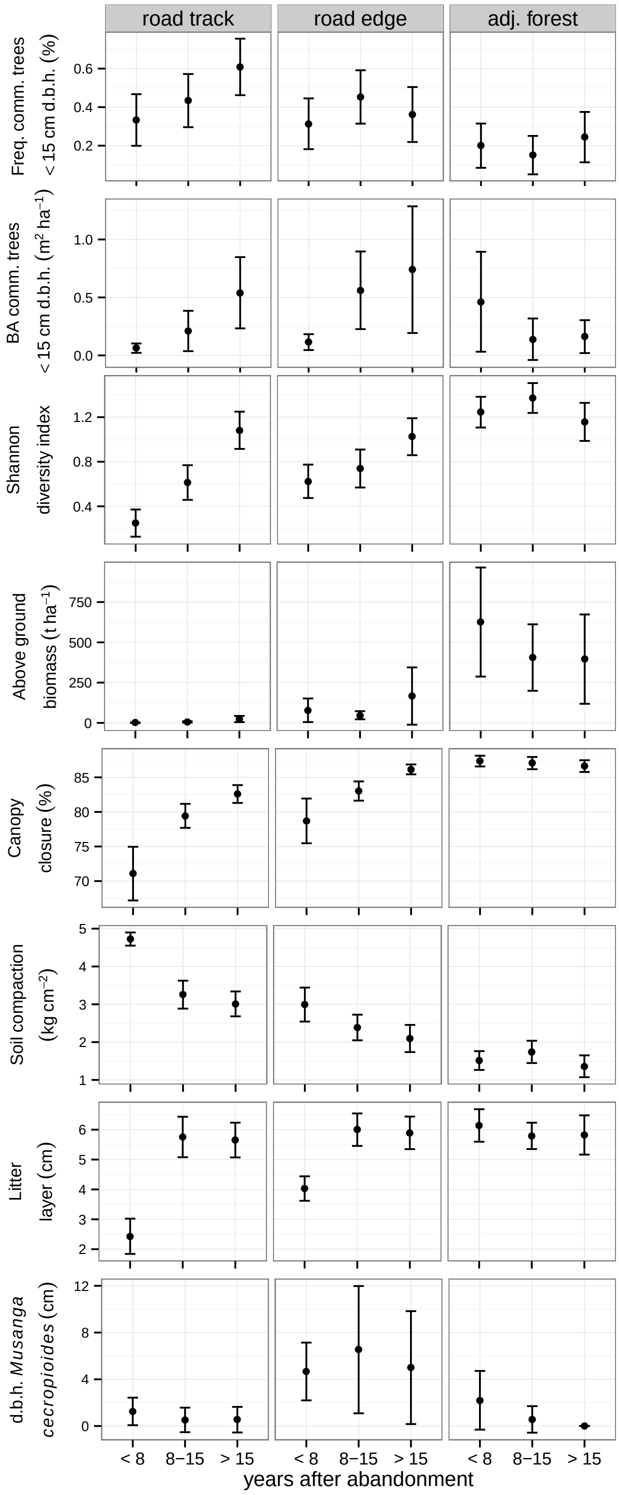

Figure 3.4 – Mean values and 95% confidence intervals for eight variables (horizontal) across plots in three habitat zones (vertical) and three road age categories (inside each box). Freq. = Frequency of presence/absence, BA = basal area of commercial species that were present, DBH = diameter at breast height. The sample size for each point lies between 44 and 53.

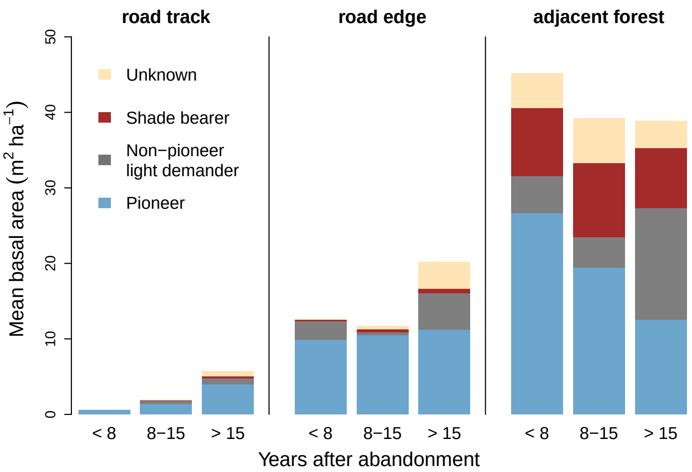

Figure 3.5 – Mean plot values of basal area of tree species regeneration guilds over age since road abandonment, in each of the three habitat zones. The unknown group consists of trees that could not be identified or those of genera that could not be assigned to a guild based on available literature and expert knowledge.

($P = 0.001$), with the greatest increase taking place in the road track (from 0.25 ± 0.12 on roads < 8 years old to 1.1 ± 0.17 in roads > 15 years old), while it did not change in the adjacent forest (from 1.24 ± 0.14 to 1.15 ± 0.17, Figure 3.4). Poor substrates had a higher Shannon diversity index than rich ones ($P < 0.001$, Supporting figure 3.9). Floristic dissimilarity based on the Jaccard index and visualized through NMDS was pronounced between the three zones for roads abandoned less than 8 years ago: With age since road abandonment, species composition in adjacent forest stayed very similar, while that in road track and edge zones remained distinct from the forest only on the first axis but underwent a clear development towards the forest on the second axis (Supporting figure 3.10, Supporting table 3.4). Basal area in all zones was mostly comprised of pioneer tree species such as *Musanga cecropioides* that thrived particularly in road edges (Figure 3.4). Fifteen years after road abandonment pioneer species accounted for 70% of the basal area in road tracks and 56% in edges. Only in the adjacent forest was the dominance of pioneer species reduced to 32%, replaced by non-pioneer light demanders with shade bearers remaining at a similar level (Figure 3.5). Due to the small plot size, species accumulation curves did not reach their saturation limit throughout all groups of samples (Supporting figure 3.11).

3.3.3 Biomass

Above-ground biomass was significantly lower in road track and edge zones (all $P < 0.001$) than in the adjacent forest but the log-transformed AGB increased significantly with time after road abandonment ($P < 0.001$, Supporting figure 3.12). For the road track this meant an increase from 1.3 ± 1.3 t ha^{-1} on roads abandoned < 8 years ago to 24.0 ± 19.35 Mg ha^{-1} on those > 15 years and for the road edge an increase from 78.3 ± 73.38 to 166.67 ± 166.67 Mg ha^{-1} (Figure 3.4). Of the total studied concession area, 190 km^2 (0.76% of the forest cover) was cleared for road construction during 1985–2015 (Supporting table 3.10). This amounts to ca. 7 500 965 Mg AGB lost through road construction or 790 Mg km^{-1}. The amount of biomass recovered through forest regrowth on road tracks older than 15 years amounts at 138 323 Mg, which is 6% of the initial amount cleared, while road edges regained 2 174 856 Mg (42%).

3.3.4 Canopy closure and soil conditions

All of the environmental variables (canopy closure, soil compaction and thickness of the litter layer) were strongly correlated with the gradient between the three zones from road track to adjacent forest and with road age (Figure 3.4). Canopy closure was lower in road track and edge (all $P < 0.001$) than the adjacent forest, but it increased significantly with road age ($P < 0.001$) such that it was very similar at ca. 80-90% in all three zones after 30 years (Supporting figure 3.12). Canopy closure was negatively correlated with clearing width ($P = 0.006$). The litter layer showed similar patterns with lower values in the road track ($P < 0.001$) and edge ($P = 0.005$) than the forest, differences that are eliminated by 30 years after the significant increase over time ($P < 0.001$). Soil compaction was higher in the road track ($P < 0.001$) and edge ($P < 0.001$) than the forest, but these differences were also reduced by the significant decrease over time ($P = 0.001$), , especially in the road track (Supporting figure 3.12). However, the value after 15 years was still more than twice as high in the road track (3.01 ± 0.33 kg cm^{-2}, Figure 3.4) as in the forest (1.36 ± 0.29). Soil compaction was lower on poor (1.23 ± 0.49 kg cm^{-2}, $P < 0.001$) and intermediate (2.06 ± 0.27, $P < 0.001$) substrates than on rich ones (2.92 ± 0.16, Supporting figure 3.9 and table 3.1).

3.3.5 Herbaceous species

The ground cover of the herbaceous non-native species *C. odorata* on the road track decreased rapidly with time after road abandonment ($P = 0.001$), from 18 ± 7.91% in the 0-8 year-old roads to 1 ± 1% after 15 years (Figure 3.6). On the road edge, its' mean cover was 5.8 ± 4.77% immediately after road abandonment and decreased to being absent after 8 years. Clearing

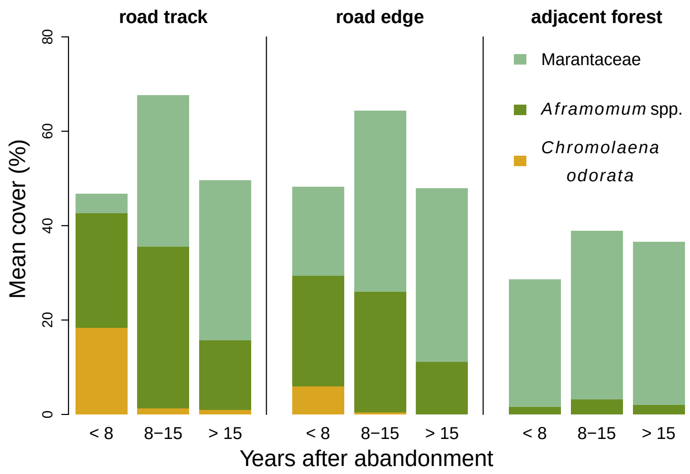

Figure 3.6 – Mean plot values of cover of three dominant groups of herbaceous plants over time after road abandonment, in each of the three habitat zones.

width had a positive effect on the cover of *C. odorata* ($P < 0.001$). In road track and edge zones the genus *Aframomum* was more abundant than in the adjacent forest ($P < 0.001$), but showed no strong trend with road age. The cover of Marantaceae increased over time across the zones ($P < 0.001$) and after eight years since road abandonment they were always the dominant herbaceous plant group with a mean cover of 35%. Their cover was significantly lower in the road track than the adjacent forest ($P = 0.002$). Cover of both Marantaceae and *Aframomum spp.* was significantly lower on poor (3% and 5%) than rich soils (31% and 19%, $P = 0.004$ and $P = 0.015$ respectively, Supporting figure 3.9 and table 3.1).

3.3.6 Access for bushmeat hunting

Of all the roads sampled, 56% did not show any sign of a path used by hunters, 26% were used as footpaths and 18% by motorcycles. The presence of footpaths was independent of road age but on roads abandoned more than 10 years ago we did not find any paths used by motorcycles because fallen trees, broken bridges and vegetation density made passage impossible. The age of roads with motorcycle paths was significantly lower than those with footpaths or no path at all (Supporting figure 3.13).

3.4 Discussion

Our results indicate that abandoned logging roads in rainforest present only a transient threat to the structural integrity of forest in the northern Congo Basin due to rapid recovery in timber stocks and tree diversity. This contrasts with earlier studies in Latin America (Guariguata & Dupuy 1997; Olander *et al.* 1998), South-East Asia (Pinard *et al.* 2000; Zang & Ding 2009) and Central Africa (Malcolm & Ray 2000). While 30 years of regeneration were not sufficient to accumulate the same level of biomass on roads as in adjacent logged forest, canopy closure, litter layer depth and herb cover converged notably. With the exception of the less exploited dense forests on poor sandstone substrates in the northern Republic of Congo, all forests in the study area have a relatively open canopy, with high ground cover of Marantaceae herbs. This forest structure has been attributed to disturbances 2500 years ago (Maley 2002) potentially linked to agricultural colonization (Bayon *et al.* 2012) followed by arrested succession. With these long-term degraded forests as a reference, there is a great capacity for forest recovery on abandoned logging roads through natural processes. We showed a clear convergence of forest structure with the surrounding old-growth forest, similar to the findings of Norden *et al.* (2009). Forest opening for road-construction has been considered the most important driver of forest degradation resulting from selective logging but, in contrast, our study does not characterize roads as triggers of a permanent regime shift in the sense of Folke *et al.* (2004). Therefore, the presence of a temporary logging road at one point in time cannot be equated with long-term forest degradation in general. This disturbance does not exceed the resilience capacity of the forest ecosystem.

3.4.1 Roads favour recruitment of timber species and recovery of biodiversity

The frequency of commercial timber species regeneration was higher in road track and edge zones than adjacent forest, just as has been shown for logging roads in Bolovia (Fredericksen & Mostacedo 2000; Nabe-Nielsen *et al.* 2007) and strip clear-cuts in Peru (Hartshorn 1989). More than 50% of the timber species found, including the most-valued *Entandrophragma cylindricum*, are classified as non-pioneer light-demanders (Hawthorne 1995). Absolute numbers were very low, as only 23 individuals $<$ 15 cm DBH of *E. cylindricum* were recorded across all three habitat zones and in 17 of the study sites. This was despite the absence of even a single tree $\geq$ 15 cm DBH of this species in the 1.55 ha of forest sample plots across the 11 studied concessions. We attribute this regeneration to the open environment of the area cleared for roads, given that seedlings of *E. cylindricum* grow well in the light conditions of small- and intermediate-sized gaps (Hall *et al.* 2003).

Concurrent with commercial species recovery we noted an increase in tree diversity, reaching a similar level in the road zones to the forest after 30 years. Road edges have been identified as particularly suitable for tree recruitment both in Central America (Guariguata & Dupuy 1997) and Central Africa

(Doucet 2004) due to the most valuable commercial species in both regions tending to be strongly light-demanding and this habitat offering both high light levels and an accumulation of topsoil from road construction. We found similar levels of commercial tree species regeneration in road track and edge zones, along with a reduction in soil compaction with age since road abandonment. The growth of diverse light-demanding tree species in the open road zones can be attributed to the combined effects of soil recovery, light availability and reduced herb competition (Marantaceae herbs had a lower mean cover on the road track than in the adjacent forest). On both the road track and edge, tree communities underwent a large turnover of notably distinct assemblies of genera with age since abandonment. Pioneer tree species remained dominant in basal area throughout the 30 years but in the adjacent logged forest we found a reduction in their basal area followed by an increase in that of non-pioneer light-demanding species, which corresponds with the expected trend of forest recovery from disturbance (Finegan 1984). At the same time both Shannon diversity and floristic dissimilarity in the forest remained at the same level over age since logging. These results indicate that recovery of the tree community on abandoned roads follows a faster trajectory than the adjacent logged forest.

3.4.2 Pronounced differences in biomass recovery

The total amount of forest clearance for road construction over 30 years in the 25 000 km^2 area of the 11 studied forest concessions resulted in approximately 13.8 × 106 Mg CO_2 being emitted to the atmosphere (assuming 50% carbon content of woody biomass). This is equivalent to the emissions of 55 000 UK citizens over the same time period (based on 250 Mg per person, data.worldbank.org). Approximately 30% of this emitted CO_2 has been re-captured through regeneration on these roads during the 30 years. However, we found strong contrasts in recovery of above-ground woody biomass between the habitat zones. Despite its increase over time, biomass on the road tracks had only recovered to 6% of average forest level between 15 and 30 years after road abandonment. Assuming linear recovery on road tracks, it would take at least 300 years until biomass stocks reach the level of adjacent forest. This estimation is at a comparable level to the results from a study in Puerto Rico (Olander *et al.* 1998) but is an even slower rate of recovery than that found for basal area on old skid trails and gaps after logging in Ghana by Hawthorne *et al.* (2012). In contrast, on road edges, with less compacted topsoil, tree basal area and canopy closure recovered much faster. Here, the accumulation of biomass during the first 30 years was dominated by fast growing pioneer species such as *Musanga cecropioides*. Projecting future development of biomass needs to consider the short life span of pioneer species and their replacement by more shade-tolerant denser-wooded species (Finegan 1984), even though this had not yet occurred up to the 30 years since abandonment of the oldest road in our study.

3.4.3 Canopy closure and herb cover converge between roads and adjacent forests

We showed that < 1% of the forest area had its canopy cover cleared for the construction of logging roads. However, we consider the average clearing width of 20 m (range 8.5–40.5) for road constructions excessive, as evidence from Brazil shows that logging roads can be operated at average clearings that are half as wide (Feldpausch *et al.* 2005). Nonetheless, even with a 20 m width the opening is only short-term, with canopy closure recovering to 83% (very close to the value in the adjacent forest) ca. 25 years after road abandonment. The extent to which roads present an obstacle for the movement of mammals (Blake *et al.* 2008) is likely to reduce over this same time-scale. Recovery of canopy cover was slowest on roads with the greatest initial width of clearance for road construction, which may be linked to the rapid establishment and persistence of a high level of cover of competitive herbaceous species restricting subsequent rates of tree establishment, especially of light-demanding species. (Honu & Dang 2002) suspected the non-native *Chromolaena odorata* to impede regeneration of valuable timber species. However, our results showed that on abandoned logging roads *C. odorata* remained abundant for less than 8 years, after which it declined to a very low level due to the shading of canopy closure and regrowing woody plants (Witkowski & Wilson 2001). But not all robust herbaceous species declined over the same timescale. Instead there was a marked turnover, with *Aframomum* species increasing in abundance after 8 years but declining after 15, whereas Marantaceae species were dominant after 15 years, reflecting their high abundance across large areas of forest landscape in the region (Brncic *et al.* 2009). The abundance of these highly competitive herbaceous species will be a major persistent factor regulating the regeneration of tree species after logging, both on roads and in the forest.

3.4.4 Contrasting succession trajectory on poor sandy soils

We detected spatial patterns in forest structure and timber species recruitment at a large scale linked to underlying geology. The sandstone plateau in northern Republic of Congo characterized by deep resource-poor soils, features a generally older, less-disturbed and slower-growing forest type (Fayolle *et al.* 2012). Here, roads tend to remain detectable for longer than in more disturbed forests on rich substrates (Kleinschroth *et al.* 2015). However, over the 12 years after road abandonment studied here on these poor soils, timber tree recruitment occurred at higher frequency and overall tree diversity was higher than on the intermediate and resource-rich soils in other parts of the study area. The different trajectory of succession on the poor sandy soils can be associated with their lower soil compaction and especially much lower abundance of competitive dominant herbs.

3.4.5 How long do logging roads remain accessible for bushmeat hunters?

Logging in the study region is nearly always accompanied by hunting (Poulsen *et al.* 2011). Commercial bushmeat hunting becomes economical on a large scale when existing infrastructure (largely logging roads) greatly reduces costs (Nasi *et al.* 2008). This is facilitated by the widespread use of motorcycles which can easily bypass barriers placed by logging companies at the junction of abandoned logging roads and permanent roads. However, we observed that following the closure of logging roads they were also abandoned by motorized poachers in < 10 years. Hunters preferentially used currently open or recently abandoned logging roads rather than old ones which would require systematic removal of vegetation and fallen trees and repair of river crossings. Logging companies are trying to ban the transport of hunters, weapons and bushmeat in company vehicles and to set up guarded barriers at entry points to forest concessions (Poulsen *et al.* 2011). However, permanently open access roads, used and maintained by logging companies, do still allow hunters to reach an extensive network of footpaths (Clark *et al.* 2009). Stricter enforcement of existing hunting regulations might disrupt the relationship between logging companies and local people (Nasi *et al.* 2008) given the region-wide importance of bushmeat (Wilkie *et al.* 2000). However, if poaching is naturally restricted to areas with current or recent logging activities, this means that the impact on wildlife occurs in limited areas in the wider forest landscape. After 10 years post-logging (one third of a 30-year rotation) logging concession areas may act as refuges from hunting with an effectiveness similar to protected areas (Haurez *et al.* 2014). Abandoned logging roads can even attract endangered species such as gorillas that feed on the abundant Aframomum and Marantaceae herbs(Matthews & Matthews 2004). We therefore recommend further research on the long-term link between abandoned logging roads and wildlife populations.

3.5 Conclusions

Abandoned logging roads are transient intensively disturbed patches in the forest landscape in the Congo Basin, with a high level of resilience shown by the vegetation components of the rainforest ecosystem but with much slower recovery of biomass on road tracks than edges. Simple improvements to forest exploitation and restoration can reduce impacts and revalorize logged forests to enhance sustainable forest management (Figure 3.7). These are: (i) to reduce the amount of biomass removal and soil compaction,

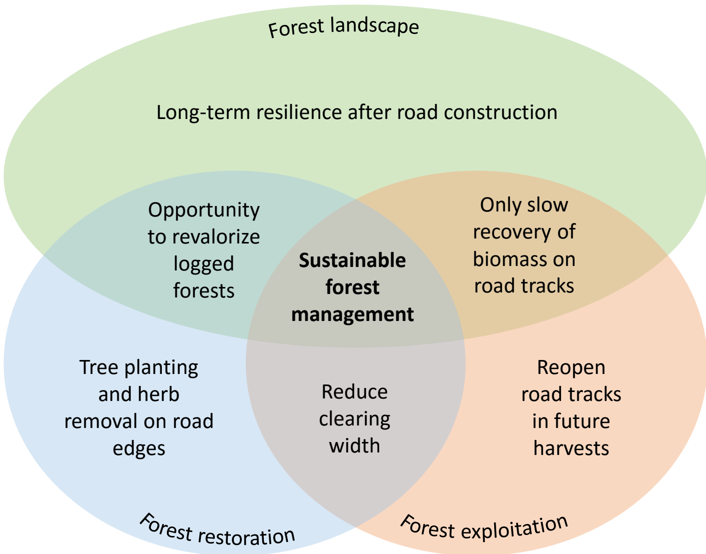

Figure 3.7 – Conceptual Venn diagram of the main conclusions. Each bubble represents one aspect of the forest: landscape, exploitation and restoration. Overlaps are labelled with potential synergies between the different conclusions.

previous roads should be reopened for subsequent harvest operations; (ii) the clearing width for road construction should be reduced markedly. The resulting reduction of exposure to sunlight that allows the road surface to dry after rain should be compensated by improvements in road maintenance and drainage; and (iii) given the high capacity of road habitats for recruitment of commercial tree species, enrichment planting trials should be established in the edge zone of recent logging roads with and without removal of competing dominant herbs as long as the road track remains accessible. If successful, once mature these trees could be harvested with low cost and impact from the reopened road track.

Data accessibility

Full inventories of vegetation and site characteristics are available from the Dryad Digital Repository: http://dx.doi.org/10.5061/dryad.51p4f (Kleinschroth *et al.* 2016b)

3.6 Supporting information

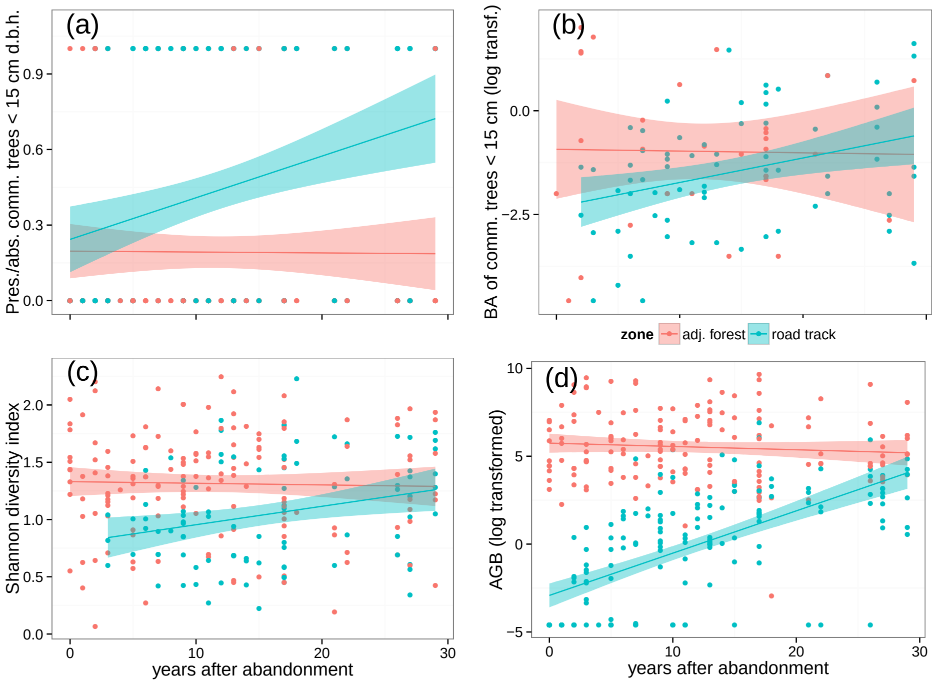

Figure 3.8 – Scatterplots against years after road abandonment of (a) the probability of presence of individuals of commercial timber species ≥ 1 and < 15 cm d.b.h., (b) log transformed basal area of the same commercial species' individuals, wherever they were present, (c) Shannon diversity index of genera of woody plants for individuals ≥ 1 cm d.b.h. (wherever present) and (d) log transformed aboveground biomass (Mg ha^{-1}) of woody plants > 1 cm d.b.h.. Colours indicate plots in the road track (blue) and the adjacent forest (red). Linear regression lines with 95% confidence intervals are included to aid visual interpretation.

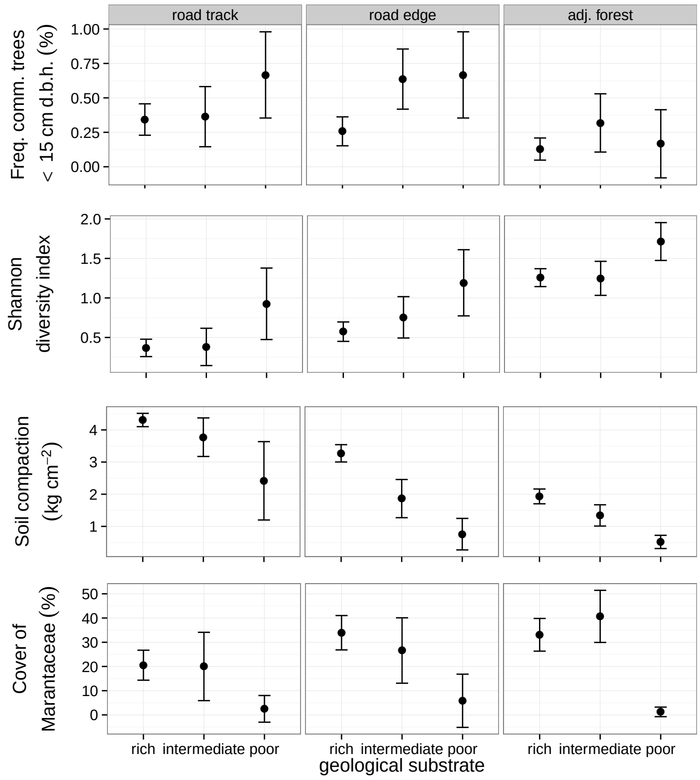

Figure 3.9 – Mean values and 95% confidence intervals for four variables across plots in three road habitat zones and three substrate fertility classes. Only plots in sites less than 15 years after road abandonment were included.

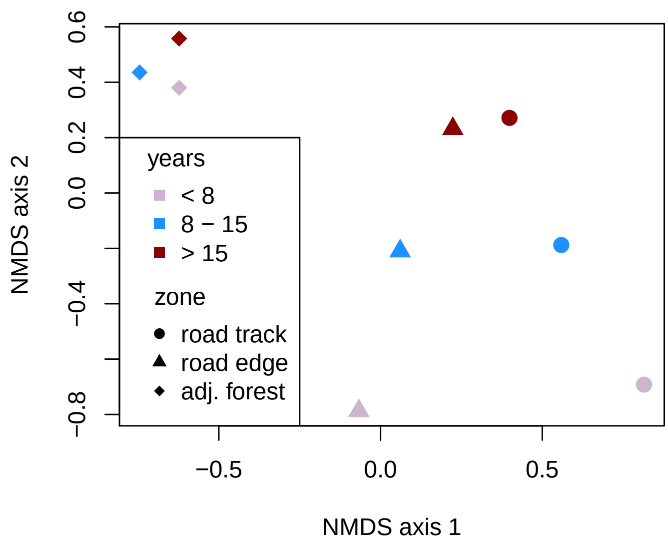

Figure 3.10 – Kruskal's non-metric multidimensional scaling based on floristic dissimilarity (Jaccard index) calculated on the presence of 173 genera in 449 plots, grouped into three habitat zones (colours) and three road age classes (shapes).

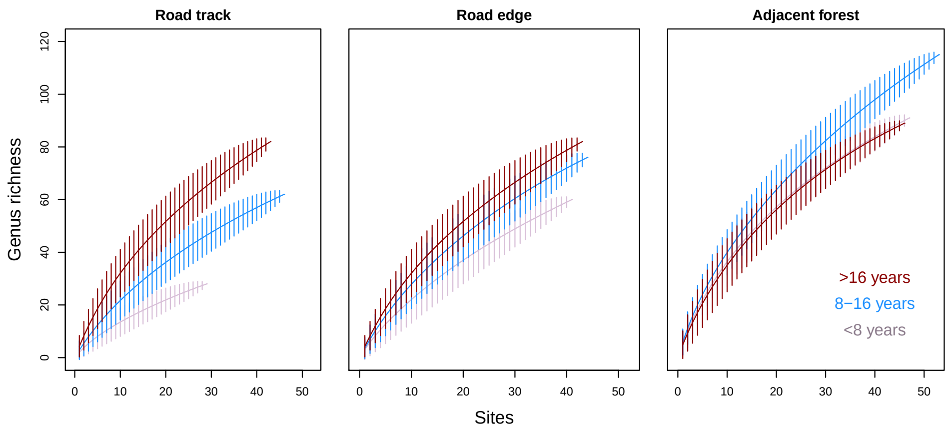

Figure 3.11 – Genus-area accumulation curves for three road age classes (in different colours) separated over each of three habitat zones.

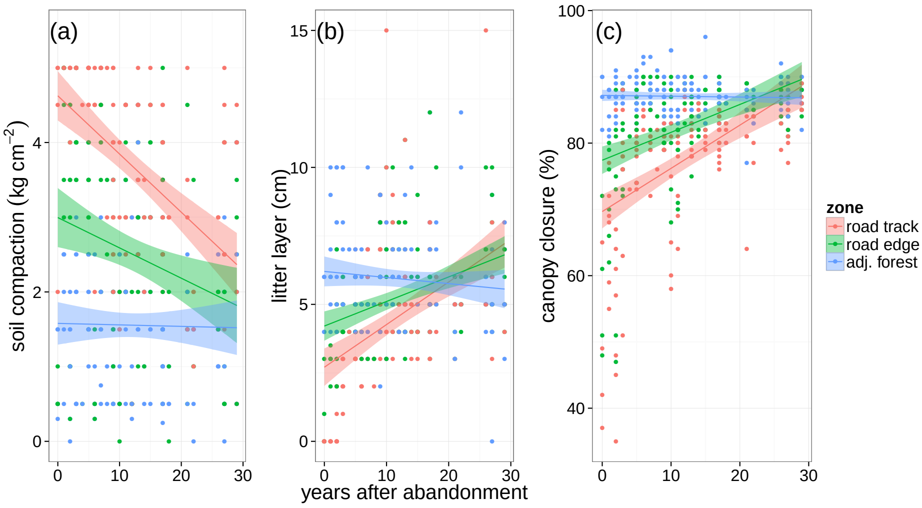

Figure 3.12 – Scatterplots against years after road abandonment of (a) soil compaction, (b) thickness of the litter layer and (c) percentage of canopy cover for three habitat zones indicated by different colours. Linear regression lines with 95% confidence intervals are included to aid visual interpretation.

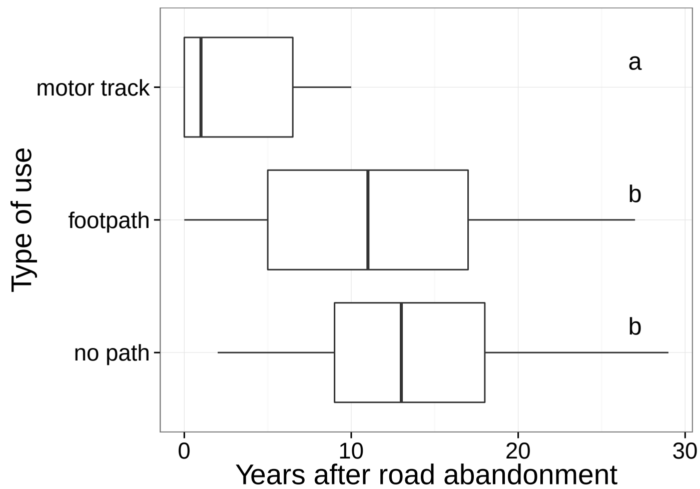

Figure 3.13 – Time since abandonment of roads with different types of path use. Small letters show significant differences with the Kruskal Wallis rank-sum test.

Table 3.1 – Mixed models of effects of environmental variables on recovery of vegetation and soils on abandoned logging roads. Each model has a different response variable but the same set of fixed-factor explanatory variables and annual felling area (AAC) as a random (nesting) factor. Ninety five per cent confidence intervals (CI) were generated through model-based (semi-) parametric bootstrapping for mixed models with 100 iterations. Model A is a generalized linear mixed model with binomial distribution, Models B to J are linear mixed models with normal distribution (for B and D achieved through log transformation). Model B contains only those plots with observations of commercial species.

Response variable	Explanatory variables	Vari-ance	Resi-duals	Estimate	95% CI	Statistic value	*P* value
A) Presence/ absence of commercial tree species < 15 cm d.b.h.	AAC (random effect)	0.77					
	(Intercept)			-1.893	-2.425/ -1.291	-6.185	<0.001***
	Years after abandonment			0.237	-0.077/ 0.534	1.536	0.124
	Clearing width			0.105	-0.259/ 0.41	0.645	0.519
	Zone (reference level: adjacent forest)						
	Road edge			1.083	0.461/ 1.544	3.728	<0.001***
	Road track			1.469	0.818/ 1.946	5.021	<0.001***
	Substrate (reference level: rich)						
	Intermediate			0.619	-0.221/ 1.609	1.393	0.164
	Poor			1.048	-0.169/ 2.302	1.766	0.077.
B) Where commercial tree species present, their basal area (log transformed)	AAC (random effect)	0	2.199				
	(Intercept)			-1.094	-1.583/ -0.532	-3.73	<0.001***
	Years after abandonment			0.445	0.176/ 0.712	3.311	0.001**
	Clearing width			0.067	-0.196/ 0.369	0.453	0.651
	Zone (reference level: adjacent forest)						
	Road edge			0.187	-0.46/ 0.791	0.55	0.583
	Road track			-0.617	-1.296/ 0.006	-1.842	0.067.
	Substrate (reference level: rich)						
	Intermediate			0.449	-0.32/ 1.095	1.216	0.226
	Poor			0.012	-0.676/ 0.742	0.029	0.977
C) Shannon diversity index of woody plant genera	AAC (random effect)	0.013	0.174				
	(Intercept)			1.269	1.174/ 1.37	28.219	<0.001***
	Years after abandonment			0.093	0.044/ 0.156	3.377	0.001**
	Clearing width			0.010	-0.047/ 0.076	0.316	0.752
	Zone (reference level: adjacent forest)						
	Road edge			-0.262	-0.378/ -0.159	-4.948	<0.001***
	Road track			-0.316	-0.425/ -0.205	-5.517	<0.001***
	Substrate (reference level: rich)						
	Intermediate			0.069	-0.101/ 0.219	0.858	0.393
	Poor			0.394	0.2/ 0.59	3.887	<0.001***
D) Above-ground biomass (log transformed)	AAC (random effect)	0.429	7.137				
	(Intercept)			5.347	4.8/ 5.932	19.651	<0.001***
	Years after abandonment			0.862	0.567/ 1.123	5.695	<0.001***
	Clearing width			-0.281	-0.612/ 0.075	-1.583	0.114
	Zone (reference level: adjacent forest)						
	Road edge			-2.892	-3.398/ -2.345	-9.39	<0.001***
	Road track			-5.451	-6.118/ -4.787	-17.671	<0.001***
	Substrate (reference level: rich)						
	Intermediate			0.400	-0.494/ 1.188	0.895	0.373
	Poor			1.168	0.047/ 2.131	2.004	0.05*

Response variable	Explanatory variables	Vari-ance	Resi-duals	Estimate	95% CI	Statistic value	*P* value
E) Canopy closure	AAC (random effect)	13	36.76				
	(Intercept)			87.225	85.337/ 88.949	104.578	<0.001***
	Years after abandonment			3.487	2.622/ 4.456	7.241	<0.001***
	Clearing width			-1.283	-2.287/ -0.273	-2.741	0.006**
	Zone (reference level: adjacent forest)						
	Road edge			-4.502	-5.698/ -2.988	-6.419	<0.001***
	Road track			-9.443	-10.79/ -7.992	-13.443	<0.001***
	Substrate (reference level: rich)						
	Intermediate			-0.943	-2.985/ 1.452	-0.658	0.512
	Poor			3.120	-0.694/ 6.965	1.556	0.125
F) Litter layer depth	AAC (random effect)	0.906	3.664				
	(Intercept)			5.914	5.453/ 6.374	24.523	<0.001***
	Years after abandonment			0.565	0.31/ 0.824	4.048	<0.001***
	Clearing width			-0.110	-0.345/ 0.191	-0.778	0.437
	Zone (reference level: adjacent forest)						
	Road edge			-0.630	-1.085/ -0.165	-2.855	0.005**
	Road track			-1.340	-1.751/ -0.897	-6.062	<0.001***
	Substrate (reference level: rich)						
	Intermediate			0.082	-0.802/ 0.888	0.203	0.84
	Poor			-0.728	-2.042/ 0.386	-1.285	0.203
G) Soil compaction	AAC (random effect)	0.182	0.925				
	(Intercept)			1.926	1.67/ 2.157	16.669	<0.001***
	Years after abandonment			-0.387	-0.523/ -0.259	-5.818	<0.001***
	Clearing width			0.084	-0.049/ 0.215	1.206	0.229
	Zone (reference level: adjacent forest)						
	Road edge			0.949	0.75/ 1.159	8.557	<0.001***
	Road track			2.125	1.898/ 2.361	19.134	<0.001***
	Substrate (reference level: rich)						
	Intermediate			-0.937	-1.295/ -0.572	-4.828	<0.001***
	Poor			-1.934	-2.388/ -1.399	-7.245	<0.001***
H) *Chromolaena odorata* cover	AAC (random effect)	31.1	112.6				
	(Intercept)			1.808	-0.673/ 4.195	1.319	0.19
	Years after abandonment			-2.598	-4.132/ -1.142	-3.276	0.001**
	Clearing width			3.677	2.105/ 5.117	4.671	<0.001***
	Zone (reference level: adjacent forest)						
	Road edge			2.121	-0.145/ 4.553	1.734	0.084.
	Road track			6.980	4.975/ 9.439	5.697	<0.001***
	Substrate (reference level: rich)						
	Intermediate			-5.461	-9.687/ -0.689	-2.359	0.02*
	Poor			-4.477	-9.851/ 1.228	-1.379	0.173
I) *Aframomum* spp. cover	AAC (random effect)	155.2	361.8				
	(Intercept)			5.869	0.558/ 11.01	2.132	0.036*
	Years after abandonment			-3.539	-6.496/ -0.527	-2.242	0.027*
	Clearing width			2.821	-0.176/ 5.394	1.933	0.054.
	Zone (reference level: adjacent forest)						
	Road edge			18.185	13.216/ 23.029	8.293	<0.001***
	Road track			22.627	18.562/ 27.457	10.302	<0.001***
	Substrate (reference level: rich)						
	Intermediate			-11.529	-20.338/ -2.825	-2.468	0.016*
	Poor			-16.862	-30.751/ -2.134	-2.51	0.015*
J) Marantaceae spp. cover	AAC (random effect)	164.8	612.8				
	(Intercept)			32.204	26.299/ 38.072	10.132	<0.001***
	Years after abandonment			7.204	3.611/ 11.038	3.919	<0.001***
	Clearing width			1.719	-2.159/ 5.589	0.938	0.349
	Zone (reference level: adjacent forest)						
	Road edge			-0.668	-5.533/ 4.55	-0.234	0.815
	Road track			-8.827	-13.952/ -3.937	-3.088	0.002**
	Substrate (reference level: rich)						
	Intermediate			1.912	-8.863/ 12.644	0.356	0.722
	Poor			-22.334	-36.82/ -6.816	-2.973	0.004**

Table 3.2 – List of commercial species with density (d) of individuals ha^{-1} and frequency (%) of plots with observations in two diameter classes and four road-habitat zones. Species names are in accordance with the African Flowering Plants database (http://www.ville-ge.ch/musinfo/bd/cjb/africa/recherche.php). Total number of 5 x 5 m plots: road track (156), edge (148), adjacent forest (156). Regeneration guild (Fayolle *et al.* 2014; Hawthorne 1995) abbreviations correspond to: P: pioneer species; NPLD: non-pioneer light demanding species; SB: shade-bearing species.

			Trees ≥ 1 and < 15 cm d.b.h.						Trees ≥ 15 cm d.b.h.					
			Road track		Road edge		Adjacent forest		Road track		Road edge		Adjacent forest	
Scientific name	Family	Reg. guild	d	%	d	%	d	%	d	%	d	%	d	%
Albizia ferruginea (Guill. & Perr.) Benth.	Fabaceae	NPLD	8	1.3	0	0	0	0	0	0	0	0	0	0
Amphimas pterocarpoides Harms	Fabaceae	NPLD	0	0	5	1.3	0	0	0	0	0	0	0	0
Cylicodiscus gabunensis Harms	Fabaceae	NPLD	0	0	0	0	0	0	0	0	3	0.6	0	0
Diospyros crassiflora Hiern	Ebenaceae	SB	3	0.6	0	0	13	1.9	0	0	0	0	5	1.3
Entandrophragma angolense (Welw.) C. DC.	Meliaceae	NPLD	8	1.9	5	1.3	0	0	0	0	0	0	0	0
Entandrophragma candollei Harms	Meliaceae	NPLD	3	0.6	0	0	3	0.6	0	0	0	0	0	0
Entandrophragma cylindricum (Sprague) Sprague	Meliaceae	NPLD	18	3.8	15	3.2	5	1.3	0	0	0	0	0	0
Eribroma oblongum (Mast.) Pierre ex A. Chev.	Sterculia-ceae	SB	5	1.3	15	2.6	13	3.2	0	0	0	0	3	0.6
Erythrophleum suaveolens (Guill. & Perr.) Brenan	Fabaceae	NPLD	0	0	8	1.9	3	0.6	0	0	0	0	0	0
Chrysophyllum lacourtianum De Wild.	Sapota-ceae		0	0	0	0	0	0	0	0	0	0	3	0.6
Gilbertiodendron dewevrei (De Wild.) J. Léonard	Fabaceae		3	0.6	0	0	22	1.3	0	0	0	0	11	1.9
Irvingia grandifolia (Engl.) Engl.	Irvingia-ceae	NPLD	0	0	3	0.6	0	0	0	0	0	0	0	0
Khaya anthotheca (Welw.) C. DC.	Meliaceae	NPLD	0	0	3	0.6	0	0	0	0	0	0	0	0
Klainedoxa gabonensis Pierre ex Engl.	Irvingia-ceae	NPLD	3	0.6	3	0.6	3	0.6	0	0	0	0	3	0.6
Leplaea cedrata (A. Chev.) E.J.M. Koenen & J. J. de Wilde	Meliaceae	SB	5	1.3	18	3.8	5	1.3	0	0	3	0.6	5	1.3
Lophira alata Banks ex C. F. Gaertn.	Ochnaceae	P	15	3.2	15	1.9	3	0.6	0	0	0	0	0	0
Lovoa trichilioides Harms	Meliaceae	NPLD	3	0.6	0	0	0	0	0	0	0	0	0	0
Milicia excelsa (Welw.) C.C. Berg	Moraceae	P	5	1.3	3	0.6	0	0	0	0	0	0	0	0
Millettia laurentii De Wild.	Fabaceae		3	0.6	15	1.9	0	0	0	0	0	0	0	0
Nauclea diderrichii (De Wild. & T. Durand) Merr.	Rubiaceae	P	0	0	28	5.1	3	0.6	0	0	0	0	0	0
Nesogordonia papaverifera (A. Chev.) Capuron ex N. Hallé	Sterculia-ceae	SB	3	0.6	3	0.6	5	1.3	0	0	0	0	3	0.6
Ongokea gore (Hua) Pierre	Olacaceae	NPLD	0	0	0	0	3	0.6	0	0	0	0	0	0
Piptadeniastrum africanum (Hook. f.) Brenan	Fabaceae	NPLD	10	1.3	0	0	0	0	0	0	0	0	0	0
Pterocarpus soyauxii Taub.	Fabaceae	NPLD	103	19.2	49	7.7	13	3.2	0	0	0	0	3	0.6
Terminalia superba Engl. & Diels	Combreta-cea	P	95	16.7	69	11.5	3	0.6	5	0.6	15	2.6	19	4.5
Triplochiton scleroxylon K. Schum.	Malvaceae	P	28	5.1	10	1.9	0	0	0	0	3	0	8	1.9
Total			321	43.6	267	35.9	97	17.7	5	0.6	24	3.8	63	13.9

Table 3.3 – Calculation of the area and above-ground biomass (AGB) of forest that has had been cleared for road construction inside the studied logging concessions during 1985-2015 based on average road clearing width and total road length. Due to low numbers of observations concessions 6 and 7, and 9 and 10 (Fig. 1) were grouped together.

Con-cession	N	Total road length (km)	Concession area (km^2)	Mean clearing width (m)	Area cleared for roads (km^2)	Proportion cleared (%)	AGB in the forest (Mg ha^{-1})	AGB removed per road length (Mg km^{-1})†
1	19	485	850	16.5	8	0.94	411	653
2	18	384	714	16.68	6.4	0.9	605	660
3	17	364	820	17.41	6.34	0.77	888	689
4	20	626	1270	16.85	10.55	0.83	544	667
5	15	165	660	16.06	2.64	0.4	151	636
6 & 7	12	357	1193	21.48	7.64	0.65	199	850
8	17	1820	5278	25.52	46.45	0.88	208	1010
9 & 10	18	2459	8536	27.9	68.3	0.86	660	1104
11	12	1564	5728	21.25	33.24	0.58	485	841
Means (SD)	15 (3)	914 (818)	2783 (2941)	19.96 (4.36)	21.06 (23.07)	0.76 (0.18)	461 (245)	790 (172)

† based on a value of 395.7 Mg ha^{-1} (Lewis *et al.* 2013)

Table 3.4 – Floristic dissimilarity between three habitats in three classes of age since road abandonment. The table is divided into Morisita-Horn (upper/right side) and Jaccard (lower/left side) indices.

		Road track			Road edge			Adjacent forest		
	Age (years)	< 8	8-15	> 15	< 8	8-15	> 15	< 8	8-15	> 15
Road track	< 8	-	0.41	0.64	0.40	0.43	0.66	0.86	0.92	0.92
	8-15	0.76	-	0.30	0.59	0.25	0.40	0.75	0.76	0.75
	≥ 15	0.83	0.64	-	0.71	0.37	0.22	0.75	0.77	0.72
Road edge	< 8	0.78	0.78	0.83	-	0.31	0.66	0.75	0.80	0.82
	8-15	0.78	0.59	0.67	0.65	-	0.28	0.60	0.60	0.61
	≥ 15	0.82	0.71	0.54	0.80	0.61	-	0.61	0.63	0.56
Adjacent forest	< 8	0.92	0.84	0.82	0.85	0.77	0.76	-	0.08	0.18
	8-15	0.94	0.86	0.83	0.88	0.80	0.79	0.44	-	0.17
	≥ 15	0.94	0.87	0.83	0.90	0.79	0.77	0.52	0.54	-

Chapter 4

Roadless space is greatly diminished by logging in intact forest landscapes of the Congo Basin

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Abstract

Tropical forest degradation is often associated with roads built for selective logging. The protection of road-free Intact Forest Landscapes (IFL) is a major biodiversity-conservation objective, and a challenge for logging concessions certified by the Forest Stewardship Council (FSC). To determine how roadless space has changed in a Congo Basin logging hotspot we developed a novel use of the empty space function, a general statistical tool from stochastic geometry and random-sets theory. This calculates roadless space based on the distance to the nearest road from any point. We compared the temporal development of roadless space in certified and non-certified logging concessions inside and outside areas declared IFL in 2000. During 1999-2007 rapid road network expansion greatly reduced roadless space in IFL. Subsequently, this trajectory levelled out in most areas, due to an equilibrium between newly built roads and abandoned roads that became revegetated. However, concessions within IFL, certified by FSC since around 2007 showed continued decreases in roadless space, thus reaching a level comparable to all other concessions. We recommend that forest management policies make the preservation of large connected

forest areas a top priority by effectively monitoring – and limiting – the occupation of space by roads that are permanently accessible.

4.1 Introduction

Road networks are expanding rapidly around the world, connecting people and resources, increasingly in remote regions (Laurance *et al.* 2014). This provides a huge challenge for species conservation as roads can act as a physical barrier to migration and therefore potentially limit gene flow, reducing effective population sizes (Benítez-López *et al.* 2010; Laurance 2015). Furthermore, roads can be corridors for species invasions into remote landscapes, with people and their vehicles acting as dispersal vectors (von der Lippe & Kowarik 2007; Veldman & Putz 2010). Consequently, roadlessness increases overall landscape connectivity for most forest species (Crist *et al.* 2005) and has been successfully used as a measure, e.g., to predict species richness and composition of Amazonian bird communities (Ahmed *et al.* 2014). Inventoried roadless areas (IRA) became part of forest and conservation legislation in 1999 in the USA due to their effectiveness for conservation outside protected areas (DeVelice & Martin 2001). Laurance et al. (Laurance *et al.* 2014) extended this approach by proposing a global strategy to regulate road building.

In tropical regions forest degradation, unregulated hunting, and deforestation due to agricultural colonization have been associated with roads built for selective logging (Brandt *et al.* 2016; Wilkie *et al.* 2000). Therefore, forest areas that are not accessible by roads are considered of highest conservation value because they provide habitats that are not immediately impacted by major human activities. The protection of such "Intact Forest Landscapes" (IFL) that are not penetrated by roads is high on the biodiversity conservation agenda. They have been defined for the year 2000 as those areas > 500 km^2 and > 10 km wide that are outside a buffer of one km around any road or settlement (Potapov *et al.* 2008). While ecologically the intactness of a forest depends on many factors, in remote tropical regions the operational use of the term "intact" corresponds to the concept of roadlessness. The underlying assumption is that important impact of roads inside intact forest landscapes are not only the dissection of formerly connected habitats but also the process of incision (Jaeger 2000) that opens the forest for anthropogenic disturbances (Laurance *et al.* 2009). Due to the easy detectability of newly constructed roads in otherwise closed canopy forests, the current identification of intact forests excludes any forest that has recently been penetrated by roads built for selective logging, independent of harvest intensity. However, e.g. in Central Africa, only 20% of roads built for logging are permanently accessible, with the remaining 80% becoming rapidly vegetated (Kleinschroth *et al.* 2015).

Forest certification, such as that of the Forest Stewardship Council (FSC), provides market-based incentives for logging operators who are audited for their sustainable forest management implying reduced impact logging standards, traceability of timber and social welfare for workers (Blackman & Rivera 2011). Adherence to these standards should require the prevention of long-term negative impacts on forest ecosystems, e.g. through poorly designed roading systems (FSC 2010). Under increasing pressure from the international environmental NGO Greenpeace, FSC has recently passed a motion to better protect IFL as part of their "high conservation value forest" policy and implement this as a new standard by the end of 2016 (Rodrigues *et al.* 2014). Central Africa, with some of the world's least exploited tropical forests, is at the center of attention for this policy change.

To quantify roadlessness in forest landscapes, new methods are required. This is essential to determine if logging operations certified for their good management did limit road network expansion. In the Sangha river catchment, a prime target area for selective logging activities in the Congo Basin, we assessed the change in logging road networks between 1999 and 2015 in order to determine how this differed between forest areas varying in certification status and location inside or outside IFL. In order to quantify and test the spatial distribution of road networks, we developed a novel use of the empty space function (F), an established mathematical tool that allows quantification and testing of the spatial distribution of roadless areas. We hypothesized that roadless space would have increased less rapidly in FSC-certified than in non-certified concessions, and even less inside intact forest landscapes, assuming a positive interaction between certification and IFL. Based on our findings we discuss the implications for forest conservation and management.

4.2 Methods

4.2.1 Study area and data collection

The study area is 107 000 km^2 in extent, covering parts of Republic of Congo, Cameroon and Central African Republic. Most of the area is characterized by Guineo-Congolian semi-deciduous forest (White 1983). This region has only recently been subject to a rapid expansion of logging road networks into previously intact forests (Laporte *et al.* 2007). These logging operations mostly take place in concessions, large state-owned forest areas that are allocated to companies for timber harvesting according to a forest management plan (Lescuyer *et al.* 2015). We analysed a total of 67 concessions of varying sizes (range 217-10 270, median 660 km^2). These are operated by 17 different companies, mostly in groups of several bordering concessions (range 365-15 560, median 1970 km^2) to reduce infrastructure costs. Between 2006 and 2009 14 concessions have been awarded FSC certification (Bayol *et al.* 2012), covering 40% of the total area of concessions. These certified concessions are operated by five different companies of which three have almost all of their concession area certified and two have only one third certified. Fifty-five percent of the study area was classified as intact forest landscapes for the year 2000 (Potapov *et al.* 2008). We classified the overall area into five different management categories: logging concessions certified or not certified by FSC, each inside and outside IFL, and national parks (Fig. 4.1).

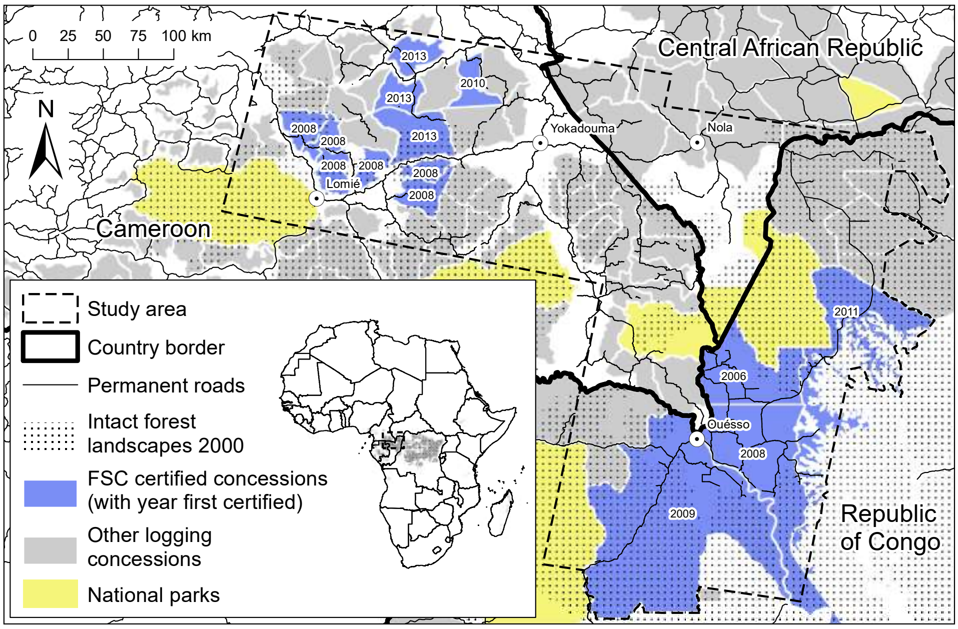

Figure 4.1 – Overview of the study area and its location on the African continent (inset). National Parks, Forest Stewardship Council certified and non-certified concessions, and their spatial overlap with intact forest landscapes as defined by Potapov et al. (Potapov *et al.* 2008) for the year 2000 are shown.

Given the economic dominance of logging in the study area, we associate the majority of roads constructed with timber extraction. Logging road networks are highly dynamic, with 50% of roads persisting on Landsat imagery for less than four years due to vegetation recovery (Kleinschroth *et al.* 2015). We vectorised forest roads during nine two-year time intervals based on a time series of 222 LANDSAT 7 and 8 images captured between 1999 and 2015. Based on the contrasting spectral properties of bare soil and recovering vegetation we were able to differentiate open (actively used) and abandoned (in process of revegetation) roads (Kleinschroth *et al.* 2015). In the present study we included only those roads that were open on any image during the 16-year time interval. The majority of logging concessions in the region are operated under a management plan, effectively limiting the amount of wood harvested annually by demarcating annual felling areas (assiettes annuelles de coupe, AAC) based on timber inventories (Karsenty *et al.* 2008). These AAC's are the most important factor determining where roads are built each year (Fig. 4.2).

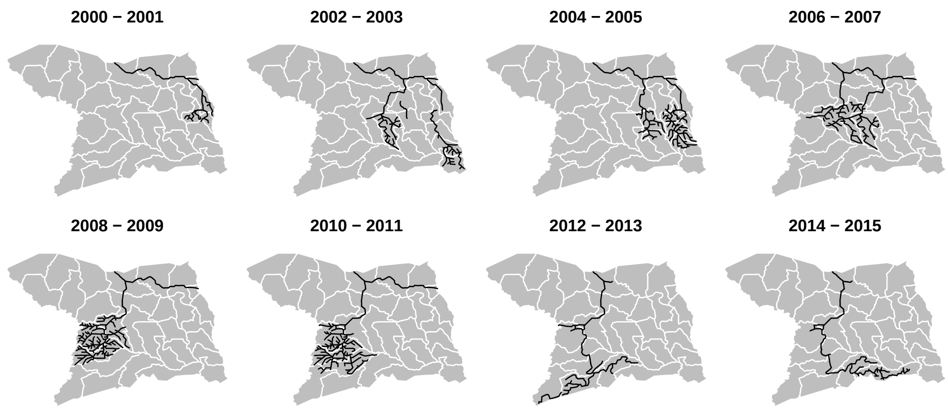

Figure 4.2 – Temporal development of the road network in one logging concession in Cameroon. White lines delimit the division of the concession into 30 annual felling areas (AAC's), black lines show roads that were open during the respective two-year intervals. The east-west extension of the concession is ca. 50 km

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4.2.2 Quantifying roadlessness with the Empty-Space Function

The method most commonly used to evaluate intactness of forests is based on one pre-defined buffer distance around any road or settlement (Herold *et al.* 2011; Potapov *et al.* 2008; Tyukavina *et al.* 2015). This approach is quick and easy but lacks accuracy in that it does not take into account the highly dynamic nature of forest degradation (Goetz *et al.* 2015). Different species have different radii of movement just as different human land uses affect forest functions over varying distances (Coffin 2007). The binary classification of an area based on a buffer (intact vs. degraded) is closely linked to road length density and does not take road location in the overall landscape into account. More sophisticated measures such as the effective mesh size (Jaeger 2000) are useful to measure connectivity in fragmented landscapes but do not respond to incision of roads into intact areas. An alternative way to characterize landscapes is to quantify, for a certain area, the distance from each point to the nearest road (Riitters & Wickham 2003). This idea is implemented in the metric of roadless volume

(Watts *et al.* 2007) where a pixel of an area is assumed to have a higher value the further away it is from a road, which then allows calculation of the volume under this pseudo-topographic surface as an index of roadlessness. We follow the approach of Riitters & Wickham (Riitters & Wickham 2003) by integrating their idea in an established mathematical function.

The Empty-Space function F (or spherical contact distribution function) is based on stochastic geometry and random sets theory (Foxall & Baddeley 2002; Gelfand *et al.* 2010; Lieshout & Baddeley 1996). The main hypothesis for our work is that that the road networks is the realization of a random set. For a stationary random set X, the distance from an arbitrary point $u \in \mathbb{R}^2$ to the nearest element of X is $dist(u, X)$. For a given radius r, F can be described as $F(r) = \mathcal{P}(dist(u, X) \leq r)$. Given the assumption of stationarity this does not depend on u. Similar to random variables, the F function can be interpreted as a moment characterizing the considered random pattern. Knowing one such moment provides a characteristic of the studied object but will not completely describe it. Nevertheless, it provides an important general feature of the entire analysed pattern, and is therefore valuable for data analysis and interpretation (Baddeley *et al.* 2006).

The observation window W serves as a sampling frame in a larger overall study area. This includes an inherent bias for the estimation of F due to the edge effect wherever the borders obscure the actual distance to an element that lies outside W. Based on the analogy with the estimation of a survival function, the distance of a reference point u to X is assumed to be right-censored by its distance to the boundary of W. Several estimators built on these ideas are available in the literature (Baddeley 1999). Here we have implemented the estimator of F given by Foxall & Baddeley (Foxall & Baddeley 2002).

We applied this type of analysis to our road networks data. The F estimation requires the evaluation of the probability that circles of increasing radii centred on any point in W intersect the line pattern. We used a toy model (Fig. 4.3) to demonstrate the use of F for linear features that can occupy a limited available space in different ways. The considered model simulates line patterns of the same length, but with a different topology. The situations depicted in Fig. 4.3 are a simple and naive replica of the characteristics of three types of network: main roads, secondary roads and rivers.

We performed multiple simulations for each model. The F function was evaluated for each model simulation on a finite set of values of r. This allowed a statistical analysis as in Illian et al. (Illian *et al.* 2008), enabling the construction of range envelopes for F, hence characterizing the linear pattern corresponding to each model. In order to synthesise all the information gathered using this statistical approach, we consider the median curve obtained from these envelopes. The results obtained from 100 simulations are given in Fig. 4.3. Clearly, the length of the line patterns is not the only ele-

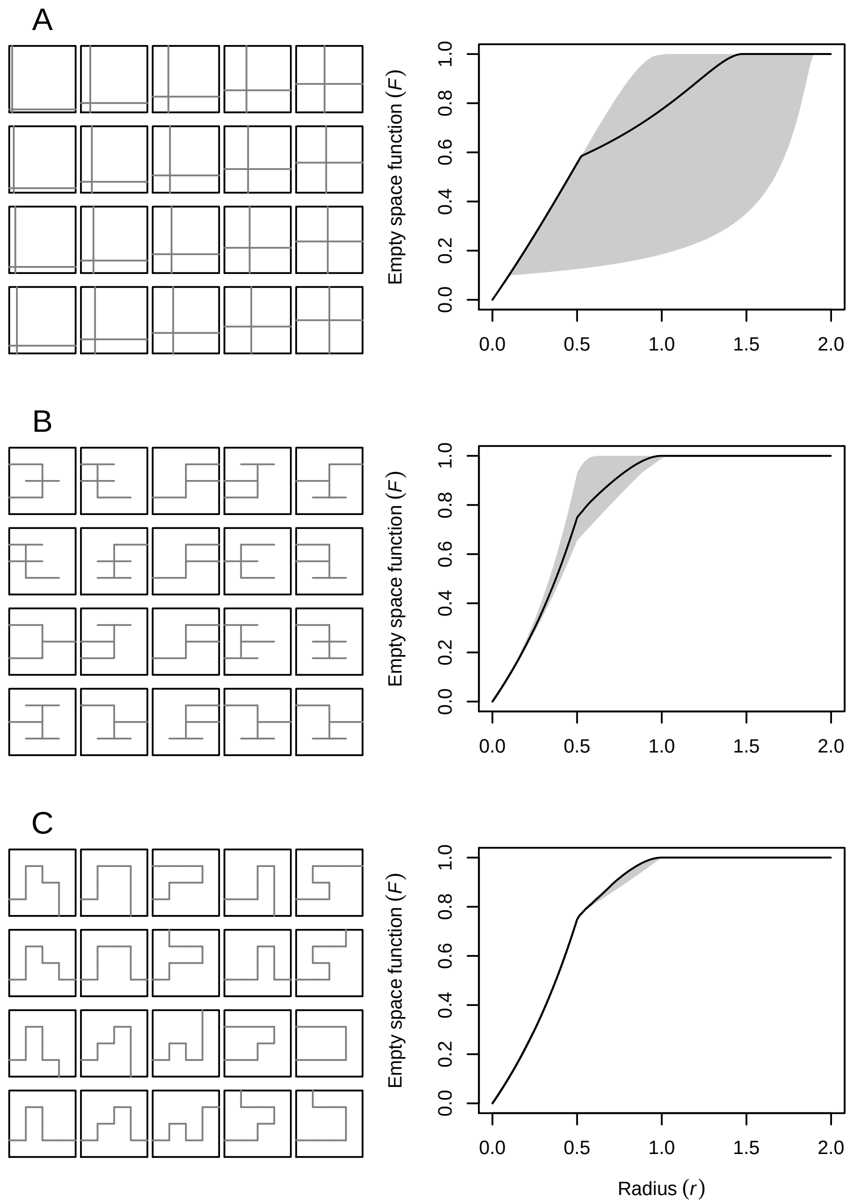

Figure 4.3 – Computation of the empty epace function F for three toy models of line patterns: (A) "main roads", (B) "secondary roads" and (C) "rivers". All patterns have the same line-length of 8 and observation windows of 4×4; 20 examples for each pattern are shown on the left. The 5-95% range envelope (grey) and the median (black) are shown on the right. The Y axes are the values of the estimation of F, and the X axes the radius r. These computations were done using 100 simulations for each model. The R codes for this example are provided in the supplementary information.

ment characterizing such an object. The F function appears to successfully integrate more information related to the entire line network topology.

4.2.3 Sampling and statistical analyses

Roadless space in the study area was calculated inside randomly placed, square observation windows. The size of each window was 30×30 km, this length being set as twice the maximum distance to a road of any point in the study area. For each year we ran 10 000 replications and kept only those windows that had at least 80% of their area in the same management/ protection status category. This gives for each year and category a number of samples n between 500 and 1000. For each replicated window we derived F. The r domain for the application of the empty space function is the interval given by $[0, 15]$ km which we divided into discrete steps of 0.2 km. Now, for year and category, for the fixed values of r, we have n corresponding values for F. Empirical quantiles were computed for each r value and, finally, the median was considered. Therefore, by considering all the medians for all the radius values, we get a median curve F for each management/ protection category. This median is denoted $\tilde{F}$.

We next compared these median curves between two management/ protection categories $\tilde{F}_A$ and $\tilde{F}_B$. The obtained functions $\tilde{F}$ are not guaranteed to be empirical distribution functions, hence an alternative to the Kolmogorov-Smirnoff test should be used. We therefore developed an alternative representation of these values: let us consider the set of differences $d_i = \tilde{F}_A(i) - \tilde{F}_B(i)$. Assuming the sample $d_i, i = 1 \ldots, n$ to be the realisation of some independent and identically distributed random variables, under the hypothesis that $\tilde{F}_A = \tilde{F}_B$, we have $E[d] = 0$. We tested this statement using a one-sided t test. Here we interpret the t test statistics as the change intensity in $\tilde{F}_B$ compared to $\tilde{F}_A$. The drawback of this test is that if the null hypothesis H_0 is not rejected, this does not mean that $\tilde{F}_A$ and $\tilde{F}_B$ are equal. Therefore, our focus lies on those cases where H_0 is rejected. For all $E[d] \neq 0$ we compared d_i between multiple categories using pairwise t test with pooled standard deviations and Holm-adjusted P values for all possible comparisons (Holm 1979).

To verify the accuracy of our methodology we first tested it on river networks. These were derived from a digital elevation model (Lehner *et al.* 2006) and thus directly reflect the topography. Despite the fundamental difference in ecological characteristics between rivers and roads, both are general random sets and can be analysed with the same tool. A priori the distribution of the rivers in the region should be independent of the management and intactness of forests. Therefore F is expected to show no difference for rivers between zones of different forest management type (because rivers are not managed in that region) but to vary for roads due to the effects of management. We duly found that empty space curves for river networks were very similar throughout all forest management categories (Fig. 4.6). Pairwise t tests showed no significant differences: P values were > 0.9 for all combinations. This does not mean that the river networks were identical but it is consistent with the assumption that the distribution of rivers is independent of forest management across the study area. This indicates that the methodology is accurate in that it does not show variation between equally distributed patterns such as the existing river network.

All analyses were carried out in R (R Core Team 2014) using the "spatstat" package (Baddeley & Turner 2005). The R codes implementing the present methodology are available by simply sending an email to the first author of this paper.

4.3 Results

In 2015 roadless space was very similar inside and outside IFL as well as in certified and non-certified areas outside national parks (Fig. 4.4 A). However, the median curve of the F-function for FSC concessions outside IFL was slightly higher than the others, indicating that this category had less roadless space. For all of the study area outside the protection of national parks we found a maximum distance of 9.8 km from any point to a road. This means that the maximum possible distance between two roads is 19.6 km. No roads were detected inside national parks (Fig. 4.4 A). Intact forest landscapes were defined based on road networks in the year 2000 (Potapov *et al.* 2008) and accordingly the F-function that we calculated also consistently showed values of zero for all concessions inside IFL in 1999 (straight lines in Fig. 4.4 B and C). Subsequently, there was a clear decrease of roadless space inside IFL over time (Fig. 4.4 B,C). Specifically, non-certified concessions (Fig. 4.4 B) showed a rapid decrease from 1999 to 2003 but in subsequent years remained on a similar level to the concessions outside IFL (Fig. 4.4 D) with a slight increase after 2009. Concessions inside IFL that have been certified since 2006 showed a slower but continuous decrease in roadless space, indicated by regularly increasing curves (Fig. 4.4 C). By 2013 these areas had reached the same level as all other concessions. Roadless space in certified and non-certified concessions outside IFL changed little between 1999 and 2015 (Fig. 4.4 D and E). Only for non-certified concessions outside IFL (Fig. 4.4 D) did the curves show a slight increase in roadless space.

Extracting the probability of encountering the nearest road within 5 km for each year illustrates continuous trends over time. In 2001 the probability of encountering a road within 5 km distance was almost 80% outside IFL and 30% or less inside IFL (Fig. 4.7 A). By 2015 it was around 60% for all management categories except for certified concessions outside IFL which showed a higher probability of around 80% (Fig. 4.7 B). In general, roadless space inside IFL decreased dramatically, with certified concessions showing a

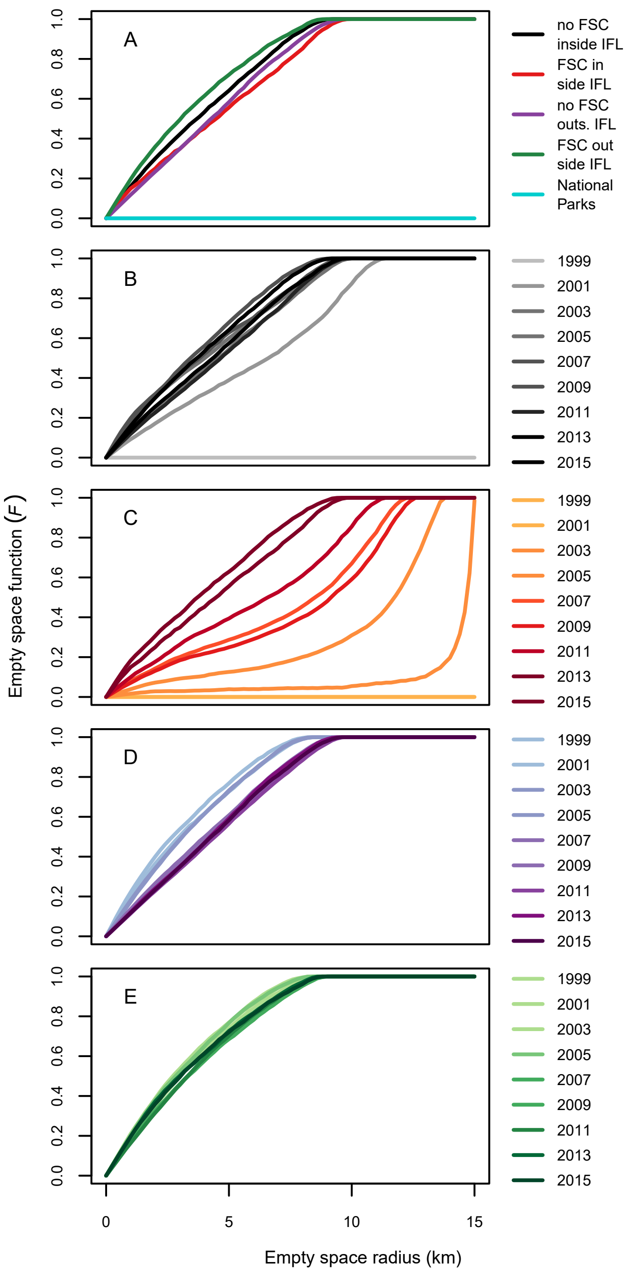

Figure 4.4 – Median curves of the Empty space function F (probability that from any point in the observed domain there is a road at distance r) against r. (A) shows the situation in 2015 for the five categories, (B) non-certified concessions inside intact forest landscapes (IFL), (C) FSC-certified concessions inside IFL, (D) non-certified concessions outside IFL and (E) FSC-certified concessions outside IFL. Panels (B)-(E) show two-year steps from 1999 to 2015 (shading from light to dark with change over time).

continuous trend until 2015. Outside IFL roadless space remained at a similar level, with a slight but continuous increase for non-certified concessions (Fig. 4.7 C-F).

Comparing changes in roadless space in two longer (eight-year) time steps highlights the contrasts amongst all four management categories. Inside IFL, roadless space decreased by more than half during 1999-2007. Then during 2007-2015 this decrease continued (at a lower rate) in the concessions that were certified from 2006 onwards, whereas it stagnated in non-certified concessions (Fig. 4.5). The change in roadless space from 2007 to 2015 was significantly different in certified concessions inside IFL from all other categories, which remained at a similar level (Table 4.1). Intensities of change in roadless space were much less outside IFL. There was a slight increase during 1999-2007, then during 2007-2015 the change intensity was close to zero with only a slight increase in non-certified concessions and a decrease in the concessions that were certified from 2006 onwards (Table 4.2).

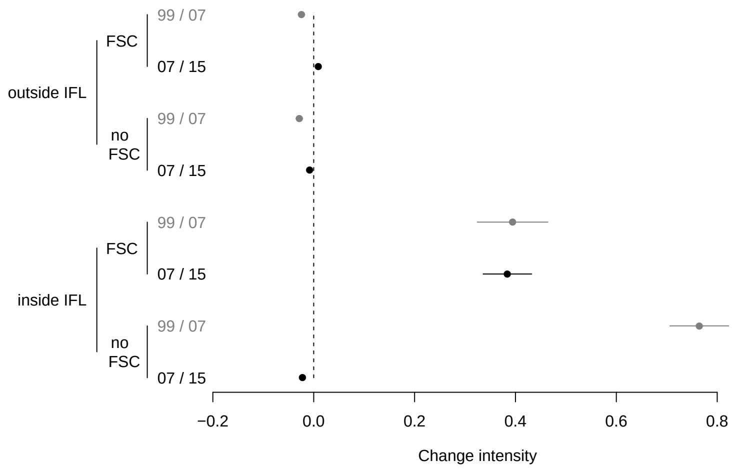

Figure 4.5 – t test statistics and 95% confidence intervals as measures of change intensity in roadless space (F) during two eight-year time periods (1999-2007, grey, and 2007-2015, black), for four management categories: logging concessions with and without Forest Stewardship Council certification (FSC and no FSC), located inside and outside intact forest landscapes (IFL). No overlap of the confidence intervals with zero indicate significant changes between the two years.

4.4 Discussion

Areas that were classified as intact forest landscapes (IFL) in 2000 are likely to be those which had been subject to least recent logging activity. With the ongoing process of governments leasing concessions for areas of unlogged forest, our result that roadless space greatly decreased inside these IFL during 1999-2007 was expected. However, that this process continued during 2007-2015 in concessions certified by FSC since 2006, whereas it stopped in non-FSC concessions, is surprising. Selective logging in the region focuses on only a few commercial timber species of high market value and expanding logging into previously unlogged areas is more lucrative than repeating logging in the same area (Laurance 2000a). However, road construction is expensive and the length of roads built is limited by the capital resources of operating companies. FSC guidelines restrict logging intensity and impose strict requirements to reduce road-related impacts such as poaching, erosion and disturbance of watercourses (FSC 2012), while recommendations about road networks only suggest avoiding "poorly designed patterns of roading" (FSC 2010). This commonly means reducing road lengths to a minimum while still allowing sufficient access to the timber resource (Gullison & Hardner 1993; Picard *et al.* 2006). However, recent discussions about certified logging in IFL highlight the importance of maximising conserved roadless space as a new component in sustainable forest management. The key consideration in choosing between different road layouts should be to retain undissected blocks of forest and this requires control of the position of permanent roads in the overall forest landscape.

4.4.1 Roadless space in certified forests decreased

The only net losses of roadless space that we recoded since 2007 took place in FSC-certified concessions. This means that in all other areas, roads that disappeared outweighed those that were newly built. This is linked with the relatively short time that logging roads remain open after abandonment (Kleinschroth *et al.* 2015). We assume that road building in each concession is related to the capital resources of the operating companies. The intensity of forest exploitation in the region is fluctuating and was strongly affected by the global economic crisis in 2009 (Karsenty *et al.* 2010) when a reduction in the volume of timber exports resulted in temporary shutdowns of logging activities. However, official wood production volume data (available at http://www.observatoire-comifac.net) shows that in subsequent years exploitation increased progressively. This was especially true for the two companies IFO and CIB, which operate four of the largest concessions in the study area, all of which obtained FSC certification between 2006 and 2009. The annual wood production volume increased by 45% from 2009 to 2013 in the IFO concession and by 24% in the CIB concessions (de Wasseige 2015). There are several potentially confounding factors that may have influenced this. Well-capitalized companies may have adopted both FSC certification and efficient means of exploitation, leading to a higher density of roads, whereas less capitalized companies did not. Logging history also differs between concession areas. In concessions that have previously been logged, there is less likelihood of yielding high timber volumes in the present cycle and therefore companies may be less likely (a) to accept the costs of FSC certification or (b) to build many new roads.

The protection of IFL has to be approached at a larger scale than individual logging concessions. Given that the extent of most IFL exceeds the size of individual concessions by far, there is still the potential to retain much greater roadless areas than can be achieved by a single operating company within one concession. The most important factor driving the reduction of roadless space is the position of roads in the overall forest landscape within which this space is located. Roads built closer to the edge have a less fragmenting effect than those in the center. Bigger concessions and those located in the center of the overall forest landscape therefore have a more important role in retaining a large contiguous area that is road-free. Annual felling areas have to be outlined in management plans before exploitation and are the determining factor for where new roads are built (Fig. 4.2)(Cerutti *et al.* 2008). So far, there is no limitation of the maximum size and position that these areas are allowed to have. Instead, FSC and other forest management guidelines focus on the annual allowable cut, the maximum volume of wood per year and minimum size of trees that are harvested (Cerutti *et al.* 2011). The environmental advantage of reducing logging intensity is equivocal if instead a greater area needs to be exploited (and made accessible by roads) in order to produce the same volume of timber as before (Healey *et al.* 2000).

4.4.2 Roadless space outside IFL is stabilizing

Outside IFL there was a low rate of change in roadless space with a small increase sustained during 1999-2015 in non-certified concessions. This represents the saturation of the forest area with permanent roads some time after the commencement of timber exploitation. It is expensive for companies to maintain and control roads that are permanently accessible and they have a strong interest in reducing the extent of open roads to the minimum that is necessary for their operational efficiency. Overall, more than 80% of all logging roads are closed and abandoned after a short period of harvesting (Kleinschroth *et al.* 2016a), a practice in accordance with recommendations for good forest management (Dykstra & Heinrich 1996). Our results indicate that, inside non-certified concessions located in areas with a longer logging history (i.e. outside IFL), in recent years the ratio between abandoned and newly created roads led to a slight increase in roadless space.

4.4.3 Minimise the dissection of tropical forests by permanent roads

We suggest to extend forest road building recommendations by taking into account the spatial layout of the road network (and thus the conserved roadless space) on regional scale. Based on our findings of limited road persistence (Kleinschroth *et al.* 2015) we suggest that logging roads should be managed as transient elements in the landscape that affect only a small part of the overall area of forest at a given point in time. Road networks should be planned so that the majority of the forest area remains inaccessible to damaging human activity (i.e. as roadless space) at all times, but the exact location of this roadless space may shift over time (Fig. 5.7). Other than the theoretical model of conservation concessions, where after a first cut the concession area becomes protected (Gullison *et al.* 2001), logging companies should be held responsible for conserving the integrity of the forest except for the small portion where logging takes place every year. Key to this integrity will be the planning and management of the road network. A particular danger is posed by permanent access roads that often transect forest areas, thus keeping the core of the forest open to permanent threats, providing pressures exist. Wherever necessary, these roads should be closed effectively and replaced by less fragmenting ones in the periphery of the forest. We suggest this as a principle for all logging road management in tropical forests.

4.4.4 Conclusions

The protection of intact forest landscapes (IFL) is currently being incorporated into FSC certification policy. Given that the extent of most IFL exceeds the size of individual concessions and frequently crosses country borders, this process affects multiple stakeholders. Based on our findings we suggest that control of the spatial arrangement of permanent roads is an essential requirement to protect IFL. We recommend that measures to reduce the impacts of selective logging should not only be based on amounts of timber extracted per time and area but also include the size of forest areas that remain undissected by roads. The preservation of large connected areas of roadless space needs to become a top priority in forest management and this can only be achieved by effectively monitoring the spatial arrangement of roads that are permanently accessible for which we advocate the use of the empty space function developed in this paper.

Supplementary information

Table 4.1 – Changes in the median empty space function $\tilde{F}$ for the road networks in each of four management categories during two time periods (years 1999-2007 and 2007-2015). P values for t tests comparing $\tilde{F}$ of different individual categories are shown (P values < 0.05 are treated as significant). IFL = intact forest landscapes in 2000; FSC = certified by the Forest Stewardship Council from 2006 onwards. National Parks were not included because no change was detected over time.

Period		IFL, FSC	IFL, no FSC	no IFL, FSC
1999 - 2007	IFL, no FSC	< 0.001		
	no IFL, FSC	< 0.001	< 0.001	
	no IFL, no FSC	< 0.001	< 0.001	0.597
2007 - 2015	IFL, no FSC	< 0.001		
	no IFL, FSC	< 0.001	0.637	
	no IFL, no FSC	< 0.001	0.138	0.067

Table 4.2 – t test statistics and 95% confidence intervals comparing changes in roadless space over time between management categories. Inputs are the median values of the empty space function F for the road networks in 1999, 2007 and 2015. The t statistic is interpreted as the change intensity. IFL = inside intact forest landscapes in 2000; FSC = certified by the Forest Stewardship Council from 2006 onwards; no FSC = not certified by FSC; CI = confidence intervals. National Parks were not included because no change was detected over time.

Category		Compared years	Change intensity	2.5% CI	97.5% CI
outside IFL	FSC	1999 / 2007	-0.033	-0.040	-0.025
		2007 / 2015	0.014	0.011	0.018
	no FSC	1999 / 2007	-0.052	-0.064	-0.041
		2007 / 2015	-0.014	-0.017	-0.011
inside IFL	FSC	1999 / 2007	0.511	0.434	0.588
		2007 / 2015	0.186	0.152	0.220
	no FSC	1999 / 2007	0.730	0.660	0.799
		2007 / 2015	0.009	0.003	0.014

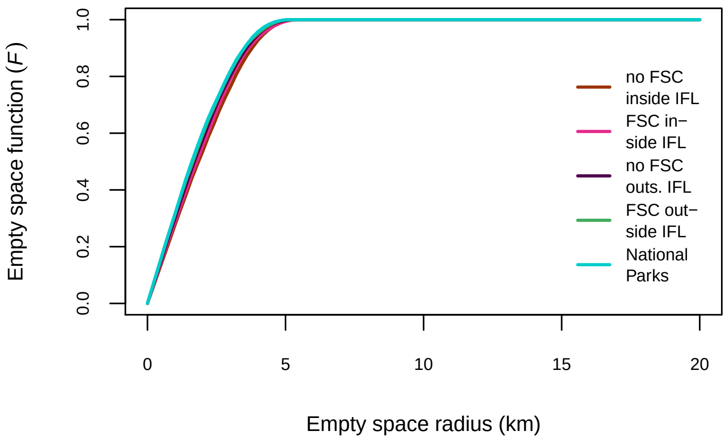

Figure 4.6 – River network analysis: median curves of the empty space function F (probability that from any point in the observed domain there is a river at distance r) against r in the five different management/ protection categories.

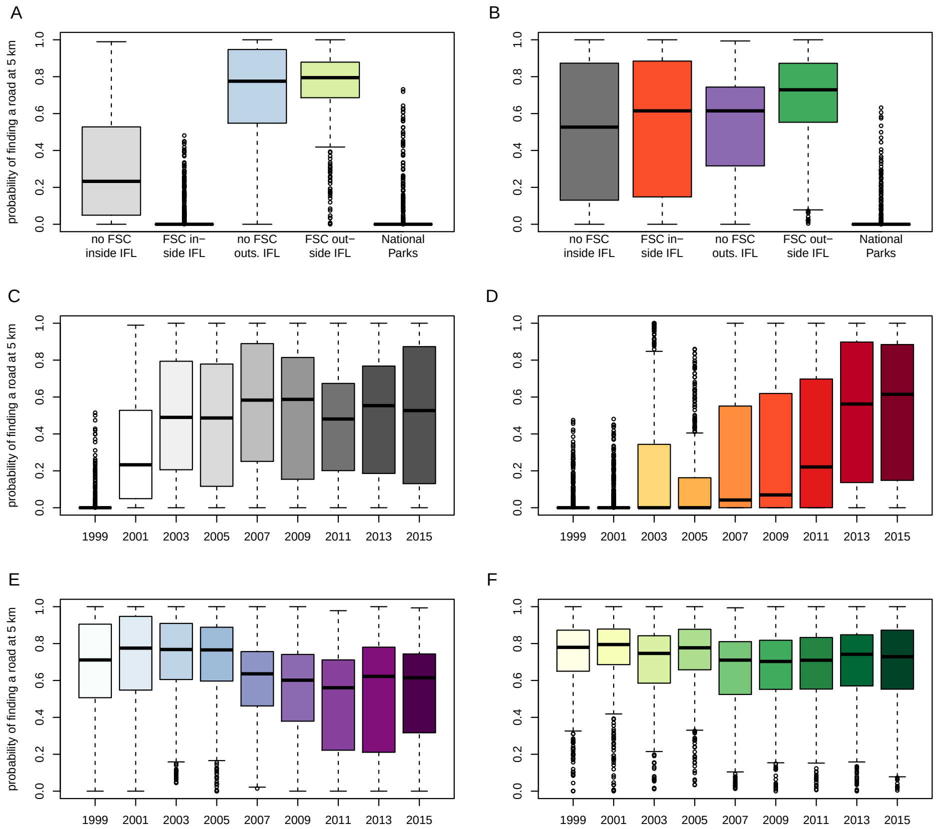

Figure 4.7 – Boxplots for the envelopes of Empty-Space curves for the probability of intersecting a road within a distance of 5 km. (A) is the combined situation in 2001 and (B) in 2015 for five different forest management/ protection categories. (C) Non-certified concessions inside intact forest landscapes (IFL), (D) FSC-certified concessions inside IFL, (E) non-certified concessions outside IFL and (F) FSC-certified concessions outside IFL. Panels (C)-(F) show two-year steps from 1999 to 2015.

Chapter 5

Road management recommendations

We identified pronounced spatial and temporal dynamics in logging road networks. A logging road that has been identified at one moment might therefore not be visible anymore at a later moment, neither on the ground nor through remote sensing. This also indicates that the area influenced by the negative impacts of roads is highly variable. These findings give novel insights and help to formulate new management recommendations for management of road networks in tropical forests. In this chapter we synthesize our findings towards recommendations in two important questions: (5.1) Should logging roads be reopened in subsequent harvest cycles? And (5.2) what is the role of permanent roads in the overall network and how can their layout in the landscape be optimised?

5.1 Sparing forests in Central Africa: re-use old logging roads to avoid creating new ones

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Selective logging is prevailing in tropical forests (Laurance & Edwards 2014) posing urgent questions of how to manage the extensive logging road networks. Bicknell *et al.* (2015) emphasized the importance of road closure after harvest operations. We agree, but logging roads should not be permanently discarded, because potentially they need to be re-used.

The presence of roads in tropical forests is often associated with negative impacts on the ecosystem through encroachment and poaching (Wilkie *et al.* 2000) and conservation scientists warn against further road expansion into high biodiversity areas (Laurance *et al.* 2014). Consequently, a motion to keep "intact forest landscapes" free from logging in certified forests has recently been passed by the Forest Stewardship Council (Rodrigues *et al.* 2014). With fewer available unlogged forests the industry will, in any case, increasingly repeat logging rotations in the same areas, despite unreliable regeneration of the most valuable, intensively harvested species. Forest management plans in Central Africa, implemented during the last 10 years, suggest a minimum of 25 years between two harvests (Karsenty *et al.* 2008). Re-using former roads in subsequent harvests reduces overall impact on the forest and may help loggers to amortize their investment in infrastructure (Holmes *et al.* 2002b). However, five decades after the start of industrial-scale logging activities in Central Africa little is known about how and where repeated logging operations are taking place. The Sangha River catchment is representative of the whole Congo Basin in that it includes both areas with long and short logging histories (Laporte *et al.* 2007). In an area covering 61 logging concessions, we carried out remote sensing and GIS analyses to identify where logging roads were located during the last 10 years relative to the historic network and how many of them were reopened or newly built. During field visits to 11 concessions spread over the study area, we conducted interviews with forest managers of the four operating companies.

Of all roads detectable in forest concessions during the last 30 years only 12% were permanent (Figure 5.1). Roads created between 2006 and early 2015 have been 75% built in roadless forest, likely to be previously unlogged. The remaining 25% have been built in previously logged areas located in 37 concessions within 1.5 km of a former, non-permanent road. Of these, on average 29% (range 0 - 74%) were reopened roads, while 71% (range 26 - 100%) were newly created. Large areas (27%) of the formerly inaccessible forest that are not protected as national parks have been penetrated by new roads since 2006. In the tradition of cut-and-run (Laurance 2000a) it still seems lucrative to open new areas where the "cream" of timber trees is still available, even if transport costs rise due to increasing remoteness. But why have new roads been built in close vicinity to previous ones? In our interviews, some logging operators indicated that they may simply have lacked information about where former roads were located. Abandoned logging roads have been described as potential sites for improved timber regeneration (Fredericksen & Mostacedo 2000), but interviewed forest managers said that this did not influence their decision-making because the time needed for a seedling to grow to harvestable size exceeds the time-scales applied in business decision-making in the region. Instead respondents stated that some former roads are intentionally not reopened because they were not sufficiently straight for fast movement of trucks and equipment.

Concentrating logging operations on existing road networks has potential advantages and disadvantages (Table 5.1). Arguably the biggest logging-related threat to biodiversity in the region is bushmeat-hunting, which is

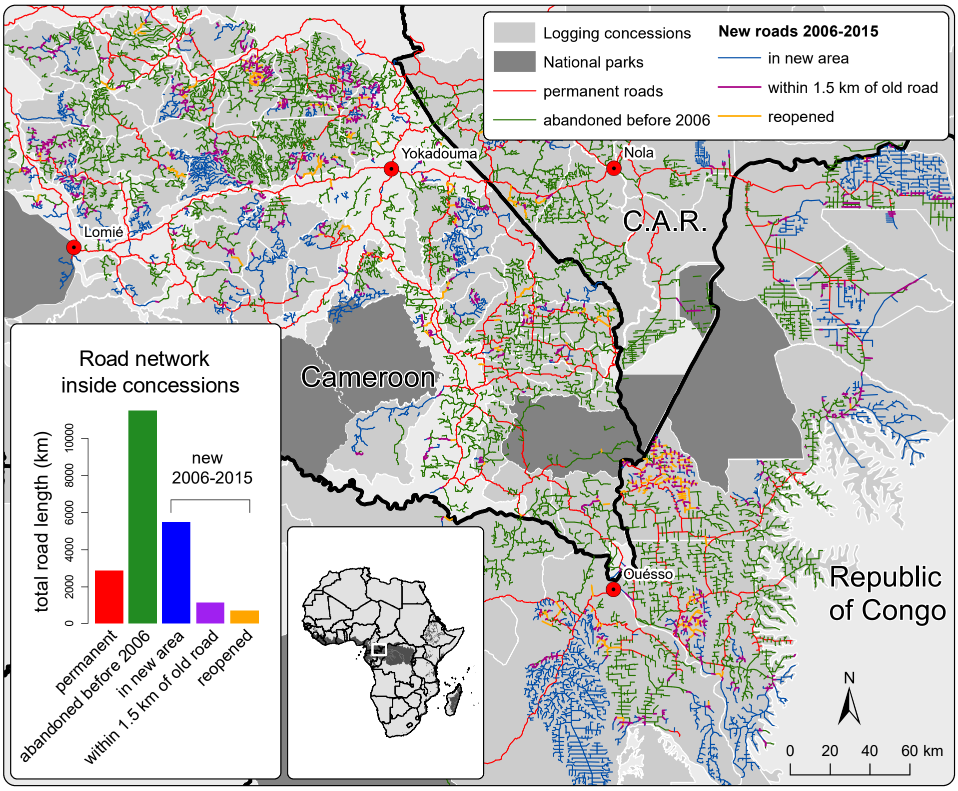

Figure 5.1 – Logging road network in an area of 108 000 km^2. Based on 222 LANDSAT images taken between 1985 and 2015 we delineated roads and determined how long they were open and when they became revegetated due to abandonment and/or closure (Kleinschroth *et al.* 2015). We grouped roads into three intervals depending on openness a) 1985-2001, b) 2002-2005 or c) 2006-2015. We then determined which roads were permanent (open in intervals a, b AND c, or b AND c, red lines), abandoned before 2006 (a AND/OR b, green), have been reopened during 2006-2015 (a AND c, orange) or were newly built during 2006-2015 (only c). We then identified which newly built roads were located in “intact” (blue) and which in previously logged (purple) areas – those within a 1.5 km buffer each side of all former, non-permanent roads (based on maximum skidding distance). Ground-truthing was done while driving along ca. 2000 km of the road network carrying out vegetation inventories on abandoned roads. Underlying logging concessions (http://www.wri.org) and national parks (www.protectedplanet.net) are shown in grey scales. Insets: Total road length for each category and location of the study area in Africa and the moist tropical ecoregion (http://maps.tnc.org).

almost impossible to regulate according to forest managers. Second-growth forests on and around abandoned roads can provide valuable habitat for species such as elephants and gorillas due to high abundance of herbaceous food plants (Matthews & Matthews 2004) while, at the same time, attracting poachers who can use former logging roads to access the forest for at least 10 years after their closure. Reopening a road can therefore have negative impacts on biodiversity (through access for hunters and loss of habitat) just as creating a new one does. On the other hand, road construction accounts for up to 40% of the costs of selective logging operations (Medjibe & Putz 2012). Reopening a former road is likely to cost much less than constructing a new one, given the lower amounts of biomass to be removed and the soil possibly still being compacted, unless the road surface has been severely eroded. Carbon emissions through forest clearing could be reduced given that the biomass accumulated on a road during the first 25 years of spontaneous re-vegetation is on average 30% of the biomass cleared for a new road (Chapter 3).

Edwards *et al.* (2014a) advocate land sparing over land sharing for logging activities. We argue that, while presenting some drawbacks, re-using logging roads can spare forests in two ways: a) within the same area by avoiding new forest clearing in the vicinity of forest previously disturbed by former roads and b) at a larger scale by sparing unlogged forests from new logging disturbance by intensifying operations on previously logged forests. To achieve greater concentration of logging activities in formerly logged areas without completely depleting timber resources, we advocate the diversification of target species and the implementation of post-logging silviculture to make repeated logging rotations sustainable. We suggest that loggers identify former road networks based on historic satellite images such as freely-available LANDSAT and plan their road network so that the major part of the forest remains inaccessible. To secure completely road-free corridors, we advocate the need for landscape-planning at a larger scale.

5.1.1 Supporting information

Table 5.1 – Overview of arguments for and against reopening of former logging roads during repeated logging cycles within previously logged areas. Arguments against reopening imply the creation of new roads.

	Reopening logging roads	
Asset	For	Against
Animal habitats		Barriers for movement of some species become hardened
		Loss of food sources for animals that are associated with previously disturbed areas
Hunting pressure	Access for hunters channelled in the same places	
	Less concentration of game attracted by food sources	
Forest regeneration	Increases potential for long-term management of post-logging silviculture	Fewer potential sites for regeneration of light-demanding timber trees on and adjacent to former roads
Biomass	Less biomass to be cleared so reduced costs and carbon emissions	
Soil	Erosion and compaction concentrated on a narrow area	Impacts are potentially less severe when spread over a wider area
Timber production		New roads can be located to improve access to remaining timber resources
Monetary costs	Reduced construction costs	Reduced transport costs due to more efficient alignment of new roads

5.2 How to keep the core of tropical forests free from permanent roads?

5.2.1 Background

A high proportion of tropical forests worldwide are selectively logged and there is a vital interest in conserving these forests as a refuge for biodiversity and for the provision of important ecosystem services. Long-term extraction of timber resources can only be sustained if it is not detrimental to ecosystem functioning. In temperate forests, a permanently accessible and maintained road network is usually considered an essential part of sustainable forestry to enable timber harvesting, ecological monitoring, hunting and recreation. This contrasts with the situation in tropical forests, where road networks built for selective logging are considered a high risk for old growth forests by opening the door for uncontrolled land use and forest degradation.

Human encroachment into unexploited rainforests generally follows a trajectory of land uses (Lewis *et al.* 2015). Logging companies are often the first to build new frontier roads into continuous blocks of intact forest forests in order to access commercial timber. Observations from Cameroon (Figure 5.2) show that permanent and abandoned logging roads are then used by hunters to access an extensive network of footpaths and motorcycle routes. In many places this leads to reduced wildlife populations even to the extent of causing so-called "empty forests" (Wilkie *et al.* 2011). Some of the hunter camps might furthermore serve as nuclei for more permanent settlements including farming of food crops using slash-and-burn agriculture (Wilkie *et al.* 2000). Shifting cultivation on a small scale has taken place in tropical forests for millennia without causing permanent damage (van Gemerden *et al.* 2003). Only the connection with main roads and markets sustains a growing human population that then potentially overuses the forest. Therefore, we argue that settlements can only be considered to threaten a forest, if they can be permanently reached by motorized vehicles. Once accessible and degraded, areas might attract the interest of investors for large scale-clearing for agricultural plantations.

We argue that the design and management of logging road networks are a key element in sustainable tropical forestry. We carried out studies on persistence of abandoned logging roads and on the spatial distribution of active logging roads in forest landscapes. This led us to the conclusion that roads in rainforests can differ fundamentally in their ecological impacts, depending on the way that they are built and maintained. Permanent roads are continuously used and maintained as main axes for access to and through the forest. Although access is often restricted by a guarded barrier, it remains questionable how successful and long-term such control can be in remote forest areas, given poor governance and high land use pressure (Figure 5.3). The majority of the logging road network consists of temporary extraction

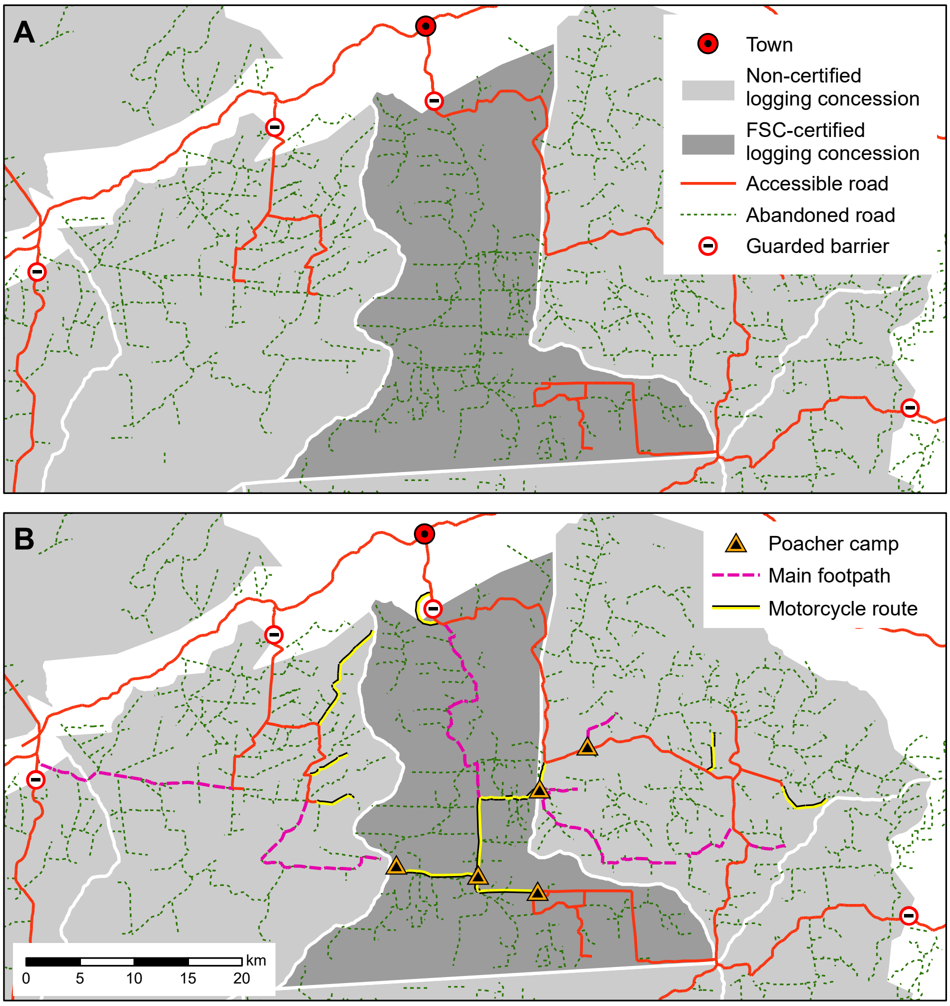

Figure 5.2 – Post-logging encroachment by hunters in forest concessions in Cameroon. (A) Officially open (red) and abandoned roads (green), (B) those abandoned roads that are used for hunting activities with motorcycles (orange) and as main footpaths (purple).

Figure 5.3 – Logs placed to block access to abandoned logging roads that have been burned by motorcycle drivers.

roads that link the timber resource with the access road. They are usually built in a ramified way with each branch leading to a number of dead-end-roads. After each harvest period, these roads are abandoned and – in a more or less effective way – closed to motorized traffic. We showed that, despite the questionable immediate success of road closure, in the long-term forest recovery makes access by motorized vehicles very difficult (Figure 5.4). We hypothesize that most non-permanent roads do not provide long-lasting threats to the forest ecosystem. However, roads that do remain accessible may act as a particular hot spot for deforestation and forest degradation. They can form a nucleus from which a new network of access routes can develop (Putz & Romero 2015). We therefore consider it crucial for sustainable forest management to control the positioning and duration of accessibility of roads, with a particular focus on roads that are accessible at the same time and so form an active network.

5.2.2 Concept

We suggest changes to the general strategy for design of roads for timber harvesting in tropical forests in order to maximise the extent of roadless space. Including the concept of intact forest landscapes (IFL) into reduced impact logging (RIL), we suggest that forest exploitation should strive to maximise the amount of roadless space at any point in time. We assume here a relatively flat area topographically, as can be found in the two big basins of the Congo and Amazon rivers, where the most detrimental geographical constraints are rivers. In other regions the topographical context

Figure 5.4 – Dense vegetation hampers the passage of a motorcycle

can be more deterministic of the road design required to minimise negative environmental impacts. In steeply sloping terrain especially, concern about the impact of roads on soil erosion and water quality is more important in determining appropriate road design (Douglas 2003; Ziegler *et al.* 2007). In those kinds of landscapes the position of roads relative to topographic features is a more important criterion.

Optimum road spacing and thus skidding distance are a function of logging intensity (quantity of wood harvested per area), road construction cost and skidding cost (Sessions 2007). If we assume an equal distribution of the timber resource, changes in road spacing at the local scale (e.g. longer distances and improved methods for skidding) can only result in small increases of roadless space on the landscape scale. Instead, we suggest that permanent access roads should be laid out close to the edges of forests blocks. The timber resources itself would be accessed through dead-end roads to be abandoned after harvest. Such major changes in road layout strategy carry potential opportunity costs for logging operators and have implications for the environment e.g. through higher carbon emissions due to longer transport distances. These costs increase exponentially with increasing size of the overall area because longer dead-end roads are required. We developed a theoretic ("toy") model with two simplified alternative scenarios (Figure 5.5 ABC), comparing the cost difference between both scenarios (Figure 5.5 D and E) and the increase of these costs with area size (Figure 5.6). We then applied this comparison to two real-world forest concessions in the

Congo Basin (Figure 5.7). Both examples use the empty space function, a tool to assess the spatial occupation of the road network (Chapter 4). This allowed us to determine how the networks are distributed at different moments in time, thus defining the extent of available roadless space.

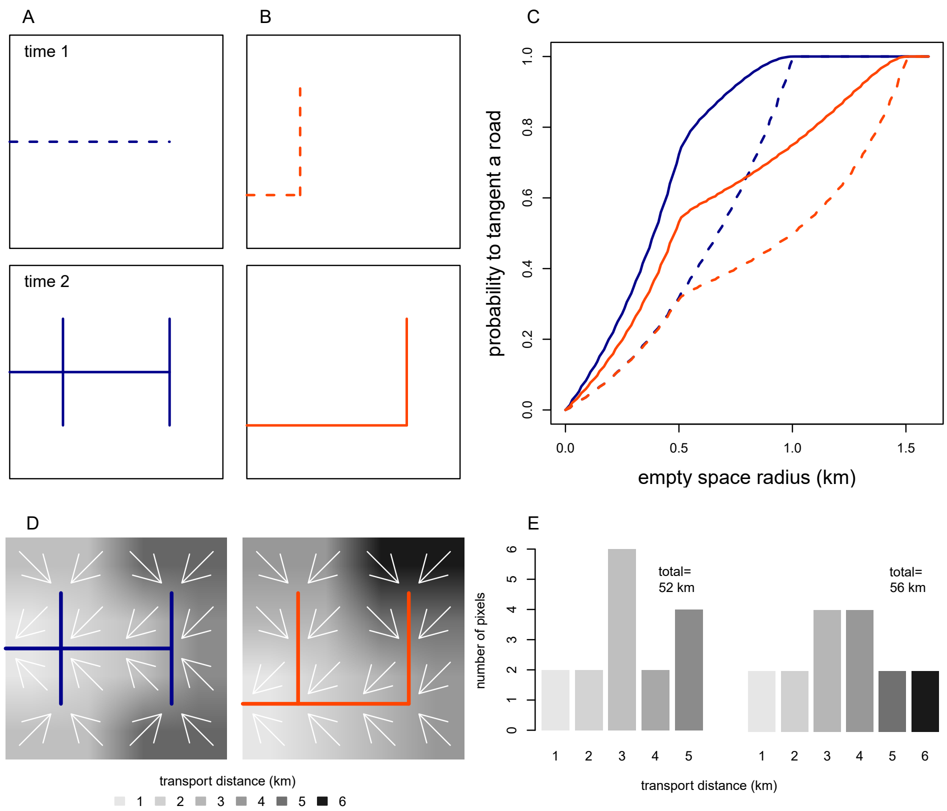

Figure 5.5 – Toy model to compare road location strategies to extract a timber resource distributed evenly across a given forest area, with no variation in skidding distance. The two contrasting scenarios are (A) a typical design with a permanent road in the center from which dead-end roads are constructed on both sides (blue) and (B) a modified design, where roads are kept closer to the forest edge (red). In (C) the roadless space is compared between the two alternatives at two points in time. Lower curves indicate more roadless space. (D) Illustrates the consequences for transport cost of the scenarios. Darker grey shadings indicate further distance from the starting point on the left side, arrows show the directions of resource extraction (skidding) on the shortest path, (E) accumulates the transport costs from D.

5.2.3 Results and Discussion

Both, the toy model and the real world examples showed lower empty space curves, and thus more roadless space, when permanent access roads are

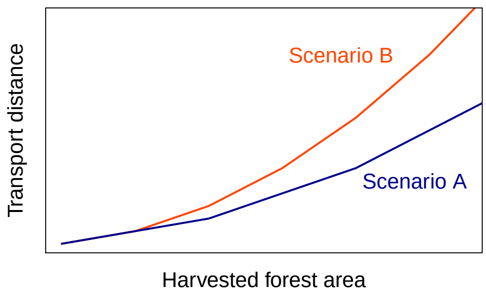

Figure 5.6 – Scale-less model of the rise in transport costs for the two scenarios from Figure 5.5 A and B with increasing size of the harvested area.

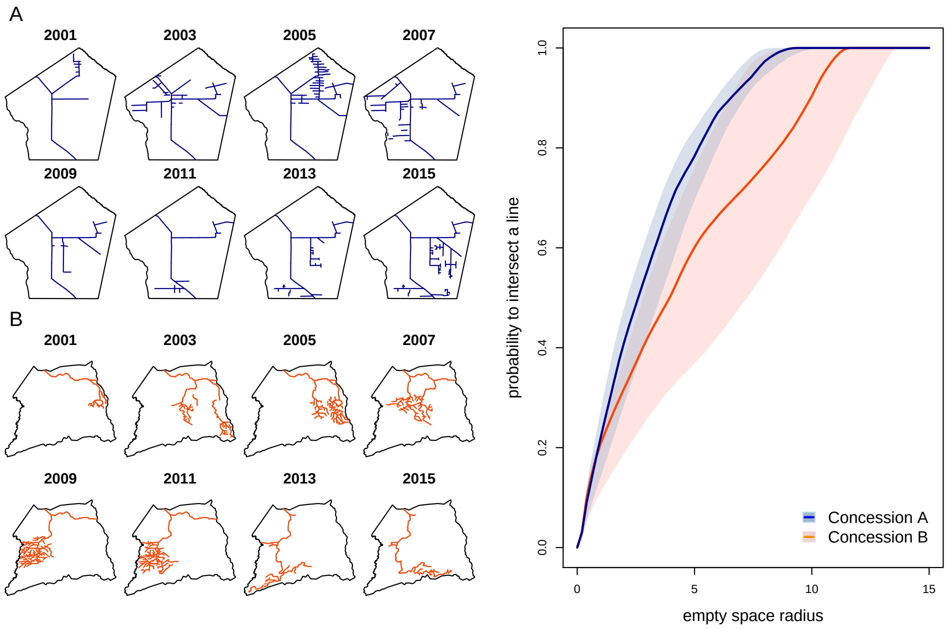

Figure 5.7 – The effect on roadless space of two contrasting road network development strategies that were implemented during timber harvesting, respectively, in two logging concessions (A) in Republic of Congo and (B) in Cameroon at two year intervals during the period 2001-2015. The two concessions were selected to be matches as closely as possible in logging history, site characteristics and area, however their boundaries are slightly modified for this modelling so that they have the same area (1227 km2) and regular shapes with a diagonal extension of ca. 50 km. The average road length for the eight sample years is 139 km for concession A and 144 km for concession B. The curves on the right show the empty space median of all years as a solid line and the 5-95% range amongst the eight sample years as shadings, indicating that overall roadless space was greater in concession B.

built closer to the forest edge (Figures 5.5 and 5.7 B). This illustrates that changes in road layout can conserve roadless space in forest landscapes without excluding large areas from timber harvest. However, such changes come with a potential trade-off in terms of financial and environmental costs. The most cost-efficient design of road networks for logging is to find the shortest possible average extraction route length per log (Picard *et al.* 2006). However, such a strategy may lead to the construction of a permanent road right in the middle of a continuous forest block with negative consequences for forest conservation due to greater fragmentation by the road itself and through the risk of encroachment that it creates. Therefore, an alternative strategy that reduces such impacts might be justifiable notwithstanding higher transport costs and transport-related greenhouse gas emissions. Placing access roads near to the edge rather than in the centre of a given forest unit means that part of the timber has to be transported on a longer route following the margins of the forest unit, rather than to the centre and then out (Figure 5.5 D). Therefore, time, costs and emissions for transport increase exponentially with the size of the area (Figure 5.6). Overall, the trade-off between, on the one hand, increased transport costs and reduced emissions, on the other hand increased roadless space.

It is possible that such a strategy could generate a compensatory increase in income through a payment for ecosystem services scheme (Busch & Ferretti-Gallon 2014) or development of forest certification standards. Improvements in the spatial design of logging road networks require forest management plans that take the overall landscape scale into account. This means that road placement and closure needs to be evaluated based on blocks of forest that remain as units in the overall landscape. However, several concessions may share such connected forest units. Any type of forest management and certification that applies only to a part of the area will lack effectiveness on the landscape scale (Yanggen *et al.* 2010).

The suggested road building strategy has two important limiting factors: (i) timber trees are rarely evenly distributed and (ii) it does not take into account geographical features such as the river network and the topography. These factors determine where roads can actually be built and how much this costs. However, e.g. in areas where steeply sloping terrain is restrictive, we see our approach as incentive tool to aid the careful evaluation which road should be maintained as permanent and which should be closed after use as temporary roads. For example, to protect soil and water quality a road that goes down a long hillslope should, ideally, not be built in the first place but, if it is, it should be used for the shortest duration possible before closure. If the road is planned to be kept permanently open, then the greater construction and transport cost of increasing its length to position it across the slope should be incurred.

Further research is necessary to model and evaluate the implementation of the suggested road layout changes on a case by case base, taking the context of land use policy, population density and existing transport infrastructure such as harbours into account. If further tests show the applicability of these improvements, it would be desirable to include them into forest certification and PES schemes.

Chapter 6

Perspectives

In this thesis I approached roads from a relatively technical point of view. I analysed their habitat potential and the contrast with the surrounding forests as well as how this contrast diminishes over time. I addressed road constructions as part of forest operations that have a financial cost and an impact on ecosystems. I analysed roads as dynamic networks that occupy the available space in a measurable way. However, I neglected the very important social side of roads. This thesis outlined, how road planning in tropical forests needs to take ecological considerations into account. However, an equal priority has to be given to the needs of local communities that grow and move in close relation with logging operations (Figure 6.1, Poulsen *et al.* 2009).

6.1 First major road corridor crossing the Congo Basin is already under construction: How to limit the impacts on the forest?

Kleinschroth, F., Healey, J.R., Karsenty, A., Forni, E. & Gourlet-Fleury, S.

In their insightful report Laurance *et al.* (2015b) highlight the environmental costs of the current boom in road construction in Africa intended to form development corridors. Road construction, like electrification, is considered a very important component of development as roads allow people in remote regions to access markets, healthcare and education. We provide evidence of the progress in constructing the potentially most controversial corridor that will eventually create the first permanent South-North crossing through the Congo Basin forest. In the African context, greater effort is needed to mitigate immediate road-related impacts rather than prioritising roadless areas on a continental scale. We show how the additional protection of relatively small areas could help safeguard large-scale conservation

Figure 6.1 – Motorcycle transporting people and forest products on a main access road inside a logging concession in Cameroon

corridors as a counterpart to road developments.

Compared to other regions in the world, Sub-Saharan Africa has higher transport costs due to the lowest provision of road-infrastructure, both in terms of quality and density (Teravaninthorn & Raballand 2009). The Trans-African Highway network (Figure 6.2 A) is an attempt to create a continuous high-quality road network that connects most African countries in order to lower costs of regional and inter-regional transport and trade (Buys *et al.* 2006). This is considered an essential basis for economic development, particularly for landlocked countries such as the Central African Republic. Major missing links in this network are in the Congo Basin forest, the second largest tropical forest in the world, which plays a crucial role in global biodiversity conservation and carbon storage (Lewis *et al.* 2009). So far, the only existing road connections here are based on logging road networks, not officially opened and maintained for public use (Kleinschroth *et al.* 2015). Laurance *et al.* (2015b) strongly argue against most roads built in the Central African forest region. They use persistent night-lights as indicators of population density that would justify road construction. However, estimates for Sub-Saharan Africa suggest that on average only 25% of the population has access to electricity (and much less in rural areas, Brew-Hammond (2010)). Even bigger towns in Africa can be completely dark at night. It seems inappropriate to systematically exclude areas without electrification from road access. Also, the reasoning that road development should be prioritised in areas with a higher agricultural potential is of little use for the 30-60 million people in Central Africa who live in forests and consume mostly forest products (Chao 2012). It is risky for nature conservation to indirectly or directly perpetuate peoples' poverty (Fyumagwa *et al.* 2013).

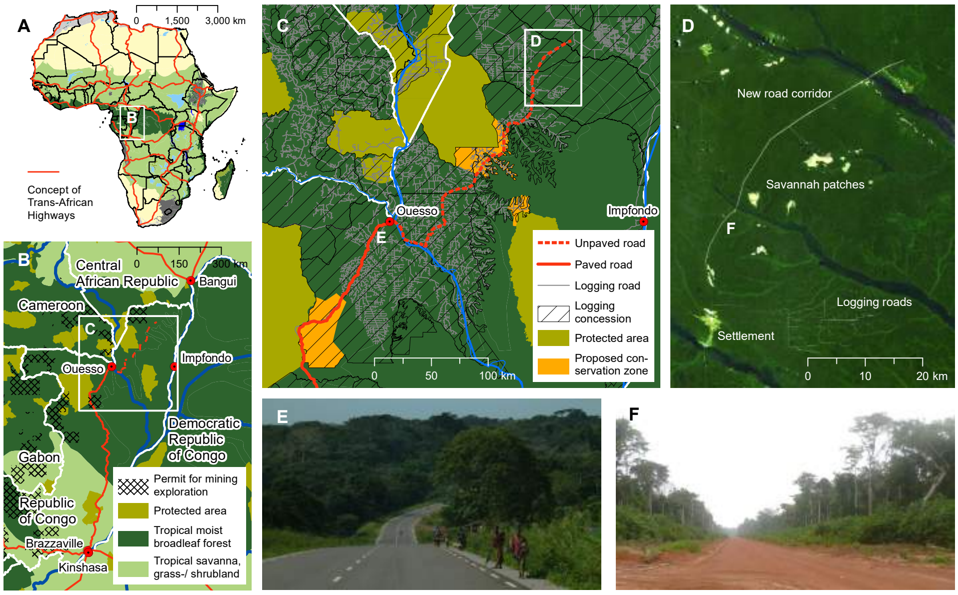

Figure 6.2 – African road planning and construction scaled down from continental to local level. (A) Overview of planned trans-African highways (UN Economic Commission for Africa, http://www.uneca.org/sites/default/files/images/tah_small-en.jpg) with underlying country borders and ecoregions (The Nature Conservancy, http://maps.tnc.org), (B) State of construction of a new public road on the Brazzaville – Bangui axis with protected areas (WDPA, http://www.protectedplanet.net) and areas with permits for mining exploration (WRI, World Resources Institute, http://www.wri.org/our-work/project/congo-basin-forest-atlases). (C) Setting of the road corridor in the northern Republic of Congo with logging concessions (WRI, as above) and old logging road networks showing the extent of forest exploitation (Kleinschroth *et al.* 2015). Existing protected areas could be extended into the orange areas to ensure conservation corridors between intact forest areas across the new road. Roadless areas in the South-East are mostly impenetrable wetlands. (D) Forest clearing (90 m wide) as a corridor for road construction, linking existing logging road networks, as seen on a LANDSAT 8 image, dated 6 April 2015. (E) Newly paved road south of Ouésso (photograph taken 17 March 2015). (F) The forest clearing for D (photograph taken 10 November 2015 at location marked F in image D).

Financed by the African Development Bank a new paved road is now under construction to link Brazzaville and Bangui, the capitals of the Republic of Congo and the Central African Republic which are currently divided by relatively inaccessible rainforest. Ouésso, a major town in the north of Republic of Congo, can already be reached by a paved road and the continuation of this axis to the North has already been built by a logging company, contracted by the government (Figure 6.2 B). This corridor is 90 m wide and recent LANDSAT images show the massive clearing of the forest for its construction (Figure 6.2 D). Closing this large gap in African road networks and creating the first South-North road crossing of the Congo Basin rainforests will be a milestone in African infrastructure development. However, the potential threat to biodiversity is very apparent as roads have been shown to trigger unregulated hunting activities, agricultural colonization and mining (Wilkie *et al.* 2000). We argue that railways present a far better alternative to cross large forest areas like this one, where the objective is to create end-end connectivity, with the minimum of environmental damage in between. However, it is also not too late to implement measures to mitigate the threats of this ongoing road building project. Due to their recognised status, new protected forest areas located adjacent to roads should be considered an opportunity rather than an effort in vain. It has been shown that roads inside protected areas present no barrier for elephant movements while in unprotected areas they do (Blake *et al.* 2008). We therefore suggest accompanying major road constructions in tropical forests with protection of the adjacent forest areas. In this process logging concessions play a key role as they can extend the conservation estate of protected areas (Clark *et al.* 2009). To create connected conservation corridors, we suggest two zones (Figure 6.2 C) where it would be particularly useful to link roadless areas across the new road. These 3200 km^2 have already been selectively logged or will be in the near future as they are part of logging concessions, in this case certified by the Forest Stewardship Council (FSC) for their sustainable forest management. We suggest this 15% of the overall concession area to become conservation zones, where concessionaires exclude any further exploitation as well as other land-uses such as mining, hunting and agriculture.

Projects such as the Trans-African Highway network are ambitious and come at a high environmental cost. Therefore, these big development projects require an integrated environmental planning component from the outset. There needs to be a strong commitment to reconcile social, economic and environmental objectives at the landscape scale, incorporating the diversity of stakeholder interests from local to global. This requires supra-regional landscape planning to evaluate impacts and prioritise the goods and services that people most depend on. Trans-African road corridors may be inevitable, but they should be accompanied by a network of trans-African conservation corridors.

6.2 Outlook

This thesis provides a first step of a landscape approach for Central Africa. More research effort is necessary to integrate a more complete range of environmental, economic and social stakeholders. For this process each chapter in this thesis hopefully provided some new answers but above all many more questions. To create a trans-African network of conservation corridors, more information is needed about wildlife migration patterns and how animal species interact with old and new roads. Mitigation schemes to guarantee such corridors require space and come with potentially high opportunity costs for other land-users. More research is therefore necessary about how payments for ecosystem services (PES) could compensate them and what role the REDD+ scheme might have in this process. Tropical silviculture is another subject that has to be developed much further. Forest management has a crucial role in reconciling different land use interests but this requires a larger set of innovative concepts to sustain forest cover and related conservation values on the long-term. Roads will continue to be of paramount interest on the nexus of human environmental systems (Figure 6.3).

Figure 6.3 – Truck transporting logs in a logging concession in Cameroon

Chapitre 7

Résumé substantiel : Routes et pistes en forêt d'Afrique centrale : l'héritage de l'exploitation forestière sélective

7.1 Introduction

Les réseaux routiers sont en pleine expansion partout dans le monde, reliant les personnes et les ressources, dans des régions de plus en plus éloignées (Laurance *et al.* 2015c). Cette expansion constitue un défi considérable pour la conservation des écosystèmes et des espèces. En effet, les routes peuvent agir comme une barrière physique à la migration et donc limiter les flux de gènes, ce qui peut avoir un impact sur la taille effective des populations (Benítez-López *et al.* 2010; Laurance *et al.* 2015a). Par ailleurs, les routes peuvent constituer des corridors pour les espèces invasives dans des paysages reculés, les humains et leurs véhicules agissant comme des vecteurs de dispersion (von der Lippe & Kowarik 2007; Veldman & Putz 2010). Par conséquent, les espaces sans route augmentent la connectivité du paysage au bénéfice de la plupart des espèces forestières (Crist *et al.* 2005). Dans les régions tropicales la dégradation des forêts liée à la chasse non réglementée, et la déforestation due à la colonisation agricole ont été associés à des pistes construites pour l'exploitation sélective (Wilkie *et al.* 2000). Par conséquent, les zones forestières qui ne sont pas accessibles par des pistes sont considérées comme présentant une valeur de conservation plus élevée, car elles constituent des habitats qui ne sont pas directement touchés par les activités humaines. Ainsi par exemple la densité routière a été utilisée comme un prédicteur de la richesse et de la composition des communautés d'oiseaux amazoniens (Ahmed *et al.* 2014). Certains auteurs proposent une stratégie globale de réglementation de la construction de routes dans les zones présentant une haute valeur pour la biodiversité (Laurance *et al.* 2014).

Une proportion importante des forêts tropicales dans le monde est exploitée de manière sélective, générant des revenus financiers qui constituent une alternative à la conversation des forêts pour l'agriculture (Asner *et al.* 2009). Cependant, des questions essentielles se posent sur la manière dont il est possible de concilier l'extraction du bois et la conservation de la biodiversité (Laurance & Edwards 2014). L'exploitation des forêts sur le long terme ne peut pas être durable si elle entraîne une altération du fonctionnement de l'écosystème, qui ne joue alors plus son rôle en termes de refuge pour la biodiversité ou de fourniture de services écosystémiques importants. Les pistes forestières sont le facteur le plus coûteux, le plus visible et probablement celui qui a les impacts environnementaux les plus sérieux, de l'exploitation sélective des forêts tropicales (Mason & Putz 2001). Dans les forêts tempérées, un réseau routier accessible et entretenu en permanence est généralement considéré comme une partie essentielle de la foresterie durable pour permettre la récolte du bois, la surveillance écologique, la chasse et le loisir. Cela contraste avec la situation dans les forêts tropicales, où les réseaux routiers construits pour l'abattage sélectif sont considérés comme constituant un risque élevé pour les forêts intactes, en ouvrant la porte à une utilisation incontrôlée des terres et à la dégradation des forêts (Laurance *et al.* 2009). Plusieurs études ont traité des effets des pistes forestières sur les écosystèmes forestiers tropicaux, mais généralement sans aborder le problème de leur persistance dans les paysages. Cet aspect est particulièrement important en Afrique Centrale, où l'exploitation sélective est le mode d'utilisation des terres le plus étendu spatialement et générateur d'importants revenus financiers. Dans cette thèse, nous analysons les dynamiques spatiales et temporelles des réseaux de pistes d'exploitation dans une partie de l'Afrique centrale, et nous formulons des propositions d'amélioration dans le cadre des aménagements forestiers. Nous traitons ce sujet en cinq chapitres, en adoptant dans chacun d'eux des angles et des échelles différents.

7.2 Les pistes forestières en forêt tropicale : Une synthèse de la littérature en Anglais et en Français met en lumière une réduction des impacts environnementaux grâce aux techniques d'ingenierie ameliorées

Dans le premier chapitre, nous présentons la littérature scientifique qui a traité des pistes d'exploitation dans les forêts tropicales. Les pistes forestières sont considérées comme des causes majeures de dégradation des forêts en raison de leurs impacts directs et indirects sur le fonctionnement et la diversité des écosystèmes. Compte tenu de l'importance de l'exploitation forestière tropicale dans le monde, la bonne gestion de l'infrastructure routière est cruciale pour réduire les impacts environnementaux associés à ces activités tout en réduisant les coûts des opérations. Notre étude visait à analyser comment la question des pistes de débardage avait été traitée dans la littérature scientifique.

Des études publiées depuis 65 ans, pour la plupart en français, dans la revue Bois et Forêts des Tropiques (BFT), ont été comparées à une série d'études plus récentes extraites des bases de données Scopus et Web of Knowledge. La moitié des articles de BFT date d'avant 1972, alors que les bases de données plus généralistes indiquent une augmentation régulière, depuis cette date, du nombre d'articles publiés sur ce thème, qui atteint aujourd'hui un niveau record. Sur l'ensemble de la bibliographie consultée, nous avons sélectionné, à des fins d'évaluation critique, 126 articles traitant des impacts et de la gestion des pistes forestières tropicales. D'une manière générale, nous avons identifié deux axes de recherche dans la littérature, l'un traitant uniquement de l'impact négatif des pistes sur les forêts et l'autre focalisé sur des recommandations plutôt techniques pour une meilleure planification, une meilleure construction et un maintien plus efficace des pistes dans le but d'en réduire les impacts. Nous avons également identifié un troisième axe, plutôt orienté sur la caractérisation de la distribution spatiale des réseaux routiers sur une échelle plus large et utilisé comme indicateur de la dégradation des forêts tropicales (Kleinschroth et al. sous presse).

Les articles de BFT se caractérisent par une attention particulière portée à des questions pratiques d'ingénierie, tandis que de nombreux articles rédigés en anglais sont consacrés à l'identification des impacts sur les écosystèmes forestiers. Les impacts environnementaux liés aux pistes forestières proviennent de la destruction du couvert pendant leur construction, de l'accroissement des effets de lisière, de l'érosion des sols, de la perturbation de la faune et de l'accès facilité aux forêts pour la chasse et la colonisation agricole. Nous présentons, sur la base de cette revue de la littérature, une liste de recommandations permettant de réduire ces impacts (Tableau 7.1).

Nous concluons que malgré un intérêt soutenu pour le sujet des pistes forestières, nous savons très peu de choses sur leur devenir à long terme dans les paysages forestiers.

TABLE 7.1 – Les problèmes environnementaux liés aux pistes d'exploitation forestière et les mesures pouvant permettre d'atténuer ces impacts. Chaque mesure n'est mentionnée qu'une fois, bien qu'elle puisse être utile pour résoudre d'autres problèmes. Une sélection des références les plus pertinentes est donnée pour chaque mesure.

Problèmes environnementaux liés aux pistes forestières	**Mesures visant à réduire les impacts**	**Références bibliographiques**
Déforestation pour la construction routière (émissions de carbone, perte d'habitat)	Réduire la longueur des pistes et des pistes en optimisant leur disposition (pour atteindre la ressource via le chemin le plus court)	Gullison & Hardner (1993); Johns *et al.* (1996); Le Ray (1959); Picard *et al.* (2006); Schulze & Zweede (2006)
	Réduire la longueur des pistes en trouvant le rapport optimal entre longueur de route et longueur des pistes de débardage	Dykstra & Heinrich (1996); Krzeszkiewicz (1959); Sessions (2007)
	Éviter la construction de pistes dans les zones à haute valeur de conservation	Durrieu De Madron *et al.* (2011); Healey *et al.* (2000); Sist *et al.* (1998)
	Autoriser des changements dans l'alignement de la route pour éviter les grands arbres	Le Ray (1959); Sessions (2007)
Effets de lisière : dessèchement , exposition au vent, mort des grands arbres	Réduire la largeur de la zone déboisée pour la construction de pistes (en moyenne 10 m, en prenant en compte l'angle solaire et l'exposition au vent)	Allouard (1954a); Dykstra & Heinrich (1996); Feldpausch *et al.* (2005); Laurance & Gomez (2005); Laurance *et al.* (2009); Sist (2000a)
Erosion des sols (et détérioration de la qualité de l'eau du fait de la sédimentation)	Adapter la localisation de la route à la topographie (emplacement sur les crêtes et parallèle aux pentes)	Allouard (1954b); Esteve & Lepitre (1972); Le Ray (1956); Pinard *et al.* (1995)

Problèmes environnementaux liés aux pistes forestières	**Mesures visant à réduire les impacts**	**Références bibliographiques**
	Limiter la pente de la route et la longueur des pistes en descente	Allouard (1954a); Le Ray (1956); Negishi *et al.* (2008); Ziegler *et al.* (2007)
	Assurer le drainage de la route par le bombement, des fossés et drains transversaux	Allouard (1954a); Dykstra & Heinrich (1996); Le Ray (1956); Putz *et al.* (2008); Sessions (2007); Sist (2000b)
	Stabiliser la surface de la route avec de la latérite	Allouard (1954b); Sessions (2007)
	Ajuster l'alignement des pistes au terrain et adopter de bonnes pratiques d'ingénierie pour protéger les pentes (par exemple minimiser les excavations sur les talus à haut risque, et stabiliser les excavations où ils ne peuvent pas être évités)	Allouard (1954b); Dykstra & Heinrich (1996); Le Ray (1956); Sessions (2007)
Altération physique des cours d'eau	Limiter le nombre des traversées de cours d'eau	Clarke & Walsh (2006); Le Ray (1959)
	Utiliser de bonnes pratiques d'ingénierie dans la construction des ponceaux, des ponts et des gués	Allouard (1954a); Douglas (2003); Sessions (2007)
	Établir des zones tampons autour des cours d'eau et des zones humides	Applegate *et al.* (2004); Pinard *et al.* (1995)
Mortalité et changement de comportement des animaux	Mettre en place des infrastructures de traversée routière (panneaux, ralentisseurs, ponts, ponceaux)	Clements *et al.* (2014); Laurance *et al.* (2009)
	Assurer des connexions aériennes dans la canopée (ponts verts)	Goosem (2007); Sessions (2007)
	Définir et contrôler les limites de vitesse	Allouard (1954a); Laurance *et al.* (2006); Sessions (2007)

Problèmes environnementaux liés aux pistes forestières	**Mesures visant à réduire les impacts**	**Références bibliographiques**
	Respecter les habitats des espèces menacées dans la planification des pistes	Clements *et al.* (2014); van Vliet & Nasi (2007)
	Limiter le nombre et le poids des engins d'exploitation	Allouard (1954a); Sessions (2007)
	Adapter la végétation en bordure de route aux préférences des animaux	Hoeven (2010)
Gestion de la chasse	Contrôler l'accès aux pistes en cours d'utilisation	Mason & Putz (2001); van Vliet & Nasi (2007)
	Fermer les pistes secondaires après la récolte à l'aide de barrières physiques et supprimer les passages de cours d'eau	Applegate *et al.* (2004); Bicknell *et al.* (2015); Sist *et al.* (1998); van Vliet & Nasi (2007)
	Interdire le transport des chasseurs et de la viande de brousse par les véhicules de l'entreprise d'exploitation	Poulsen *et al.* (2009); Robinson *et al.* (1999); Wilkie *et al.* (2000)
Colonisation agricole	Planifier et réglementer l'utilisation des terres, fournir des alternatives pour les colons	Chomitz & Gray (1996); Dykstra & Heinrich (1996); Laurance *et al.* (2014); Mertens & Lambin (2000)

7.3 Zone d'étude

La zone d'étude couvre 107 000 km^2 et s'étend sur une partie de la République du Congo, du Cameroun et de la République Centrafricaine. La plus grande partie de la région est couverte par la forêt semi-décidue Guinéo-Congolaise (White 1983). Cette région a récemment fait l'objet d'une expansion rapide de l'exploitation forestière et des réseaux routiers dans des forêts auparavant intactes (Laporte *et al.* 2007). Les opérations forestières se déroulent principalement dans des concessions, vastes zones forestières appartenant à l'État qui sont attribuées aux entreprises pour la récolte de bois selon une gestion forestière aménagée. Nous avons analysé un total de 67 concessions de tailles différentes (de 217- à 10 270 km^2, médiane 660 km^2). Celles-ci sont exploités par 17 entreprises différentes, la plupart du temps dans des concessions adjacentes (de 365 à 15 560 km^2, médiane 1970 km^2) pour réduire les coûts d'infrastructure. Entre 2006 et 2009, 14 concessions ont été certifiées « Forest Stewardship Council » (FSC) (Bayol *et al.* 2012), cette certification couvrant 40% de la superficie totale des concessions. Ces concessions certifiées sont exploitées par cinq compagnies différentes dont trois ont la quasi-totalité de leur zone de concession certifiée et deux seulement un tiers. Cinquante-cinq pour cent de la zone d'étude a été classée en « paysages forestiers intacts » (IFL ou « Intact Forest Landscape ») pour l'année 2000 (Potapov *et al.* 2008) (Figure 7.1).

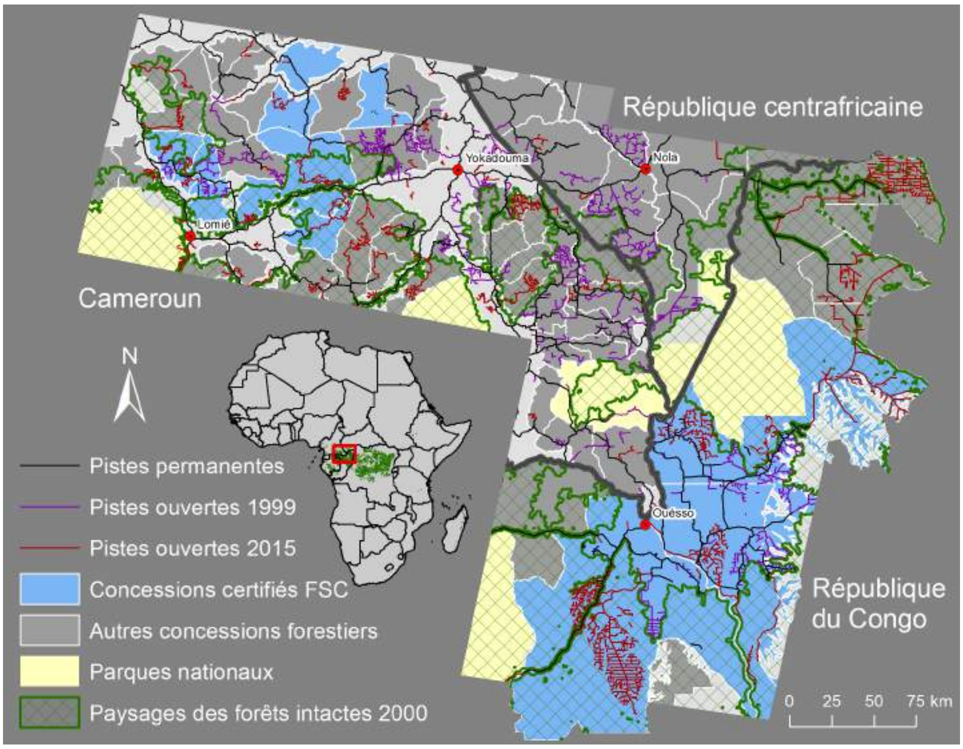

FIGURE 7.1 – Zone d'étude et positionnement en Afrique centrale des concessions forestières selon leur certification FSC , et par rapport aux paysages de forêts intactes.

7.4 Heritage laissé par les pistes d'exploitation forestière dans le bassin du Congo : Comment les cicatrices dans le couvert forestier evoluent-elles ?

Dans le deuxième chapitre nous présentons la méthodologie, basée sur l'utilisation d'images satellitaires LANDSAT, qui nous a permis d'identifier les routes et pistes d'exploitation, primaires et secondaires, en Afrique centrale. Les routes et pistes forestières sont souvent associées à la dégradation des forêts par la fragmentation et l'accès à d'autres utilisations des terres. Cependant, dans les concessions gérées pour la production de bois, les pistes secondaires sont habituellement fermées après exploitation et devraient disparaître avec le temps. On a peu d'information sur l'efficacité de cette prescription des plans d'aménagement et sur les facteurs qui influencent la reconstitution de la végétation sur les pistes d'exploitation forestière abandonnées. Nous avons utilisé une méthode innovante d'analyse des pistes forestières, considérées comme des éléments temporaires dans le paysage forestier dont la persistance varie en fonction des conditions environnementales.

Nous avons analysé la persistance des pistes au cours de la période 1986-2013 dans des zones adjacentes du Cameroun, de la République Centrafricaine et de la République du Congo. Trois stades de reconstitution successifs de la forêt sur les pistes ont été identifiés sur les images LANDSAT : pistes en activité, dont le sol est nu, pistes en cours de revégétalisation après abandon et pistes ayant disparu et ne se distingant plus de la forêt avoisinante. Des inventaires sur le terrain ont confirmé des différences significatives entre les trois catégories de pistes du point de vue de la densité et de la richesse en espèces ligneuses, ainsi que du couvert herbacé dominant. En utilisant une série chronologique d'images, nous avons réalisé une analyse de survie pour évaluer la dynamique temporelle des pistes secondaires au cours des 30 dernières années. Nous avons utilisé comme unités d'échantillonnage des segments de piste se terminant en « cul-de-sac », exclusivement construites pour l'exploitation du bois. Seuls 6% de ces segments ont été identifiés comme réouverts au cours de la période considérée. L'analyse de survie a montré une persistance médiane de quatre ans pour les pistes en activité, avant de passer au stade « piste en cours de revégétalisation », et de 20 ans pour les pistes en cours de revégétalisation avant de disparaître (Kleinschroth *et al.* 2015). 2015).

Nous avons montré que la persistance des pistes dépendait en partie de différents facteurs environnementaux, en particulier des substrats géologiques. La persistance des pistes en cours de revégétalisation est de 25% plus longue sur des substrats géologiquement pauvres, du fait d'une fermeture plus lente de la forêt dans les zones peu fertiles. Nous avons mis en évidence une différence du potentiel de reconsitution, une fois les pistes abandonnées, entre les forêts qui poussent sur différents types de substrat. Les plans d'aménagement forestier devraient prendre ces éléments en compte. Les activités d'exploitation devraient être concentrées sur le réseau routier existant et l'exploitation sur les sites situés sur les sols pauvres devrait être moins intense.

7.5 Comment les pistes d'exploitation forestière affectent-elles la végétation en Afrique Centrale ?

Dans le troisième chapitre, nous analysons la persistance des pistes d'exploitation sur le terrain. Les pistes forestières peuvent enclencher un processus de dégradation des forêts tropicales en réduisant l'intégrité de l'écosystème et en créant des accès pour la chasse. Par conséquent, la gestion des pistes est essentielle pour concilier l'exploitation sélective du bois et la conservation de la biodiversité. La plupart des pistes d'exploitation est abandonnée après la récolte du bois. Cependant, on connaît mal leurs impacts à long terme sur la végétation forestière et l'évolution de leur accessibilité, en particulier en Afrique centrale.

Nous avons réalisé des inventaires de végétation sur des pistes plus ou moins anciennement abandonnées (entre 1985 et 2015, donc depuis 30 ans, jusqu'à cette année). Dans 11 concessions forestières dans le Bassin du Congo, nous avons échantillonné une chronoséquence de pistes qui, d'après l'analyse des images satellitaires, ont été abandonnées entre 1985 et 2015. Nous avons inventorié la régénération des arbres commerciaux la diversité des espèces ligneuses présentes ainsi que la biomasse aérienne sur trois zones : la bande de roulement, le bord de la piste (où la forêt a été détruite au cours de la construction de la piste) et la forêt avoisinante exploitée (Kleinschroth *et al.* 2016b).

Les résultats montrent que la bande de roulement et le bord des pistes constituent des habitats particulièrement favorables pour la régénération des espèces commerciales, tout en étant soumis à des modifications rapides des conditions environnementales. La densité des espèces commerciales $\leq$ 15 cm de diamètre s'est avérée presque trois fois plus élevée sur la bande de roulement (327 individus ha^{-1}) et le bord des pistes (278) que dans la forêt adjacente (111). Avec le temps, la diversité des espèces ligneuses évolue vers un niveau comparable entre les pistes et les forêts avoisinantes, en même temps que la canopée se ferme.

La largeur moyenne d'éclairement adoptée lors de la construction des pistes s'est avérée être de 20 m, couvrant un total de 0,76% de la superficie des forêts à l'intérieur des concessions. Sur les pistes les plus anciennes, abandonnées il y a 30 ans, un tiers de la biomasse perdue lors de la construction a été reconstituée du fait de leur ré-végétalisation. Cependant, nous avons observé des différences importantes entre les trois zones inventoriées. Quinze ans après leur abandon, les bandes de roulement avaient récupéré 24 Mg ha^{-1} de biomasse ligneuse, soit 6% de celle présente dans la forêt avoisinante, tandis que les bords de piste avaient accumulé 167 Mg ha^{-1} (42%). Dix ans après abandon, les pistes ne sont plus pénétrables par des braconniers sur motocyclettes. Par ailleurs, l'espèce exotique Chromolaena odorata est complètement remplacée par les Marantaceae, dont l'abondance est encore plus élevée dans la forêt avoisinante.

Nos observations sur la reconstitution de la végétation suggèrent que les pistes d'exploitation forestières sont essentiellement des éléments transitoires dans les paysages forestiers. Toutefois, étant donnée la lenteur de reconstitution de la biomasse sur les bandes de roulement abandonnées, nous préconisons à la fois 1) de diminuer la largeur de dégagement utilisée pour la construction des pistes et 2) la réouverture de vieilles pistes d'exploitation pour les récoltes futures, plutôt que de construire de nouvelles pistes dans les forêts intactes. Les bords des pistes semblent appropriés pour des interventions post-exploitation, comme par exemple des plantations d'enrichissement associées à la suppression des herbes dominantes durant les premières années après l'abandon des pistes, à un moment où la bande de roulement est encore accessible.

7.6 L'espace sans routes et pistes se reduit dans les paysages de forêts intactes d'Afrique centrale, du fait de l'exploitation forestière

Dans le quatrième chapitre nous analysons l'extension du réseau des pistes, à l'échelle du paysage. La dégradation des forêts dans les tropiques est souvent associée aux pistes construites pour l'exploitation sélective. La protection de paysages forestiers intacts (intact forest landscapes ou IFL) qui ne sont plus accessibles par des routes ou pistes est un élément clé pour la conservation de la biodiversité, et un défi pour les concessions forestières certifiées par le Forest Stewardship Council (FSC). Sous la pression croissante de l'ONG environnementale Greenpeace international, le FSC a récemment adopté une motion visant à mieux protéger les IFL dans le cadre des "forêts à haute valeur de conservation" (Rodrigues *et al.* 2014). L'Afrique centrale, avec des forêts encore moins exploitées que dans les autres régions tropicales, est au centre de l'attention portée à ce changement possible de politique.

Un objectif de conservation fréquemment énoncé est de maximiser la rétention d' « espace sans routes », un concept basé sur la distance entre tout point et la route la plus proche. L'hypothèse sous-jacente est que l'impact des routes sur les paysages forestiers intacts n'est pas seulement dû à la dissection d'habitats auparavant connectés, mais aussi au processus d'incision (Jaeger 2000) qui ouvre la forêt aux perturbations anthropiques. Du fait de la facilité de détection des routes et des pistes dans les forêts ayant une canopée fermée, l'identification actuelle des forêts intactes se fait en excluant toutes les forêts situées dans une zone tampon d'un kilomètre autour des routes et pistes construites pour l'exploitation sélective, indépendamment de l'intensité de la récolte. Cependant, en prenant l'exemple de l'Afrique centrale, seulement 12% des pistes construites pour l'exploitation forestière sont accessibles en permanence, le reste (88%) se re-végétalisant rapidement (Kleinschroth *et al.* 2016a).

Pour quantifier l'espace sans routes dans les paysages forestiers, de nouvelles méthodes sont nécessaires. Cela est essentiel pour déterminer si les compagnies forestières certifiées pour leur bonne gestion ont réduit spatialement l'expansion du réseau routier. Nous avons utilisé pour cela une méthode originale, basée sur l'utilisation – pour la première fois en foresterie - de la formule dite « de l'espace vide » (empty space function). Cette formule résulte d'une extension aux deux dimensions d'une formule permettant d'analyser des processus ponctuels et présente l'avantage d'être mathématiquement bien définie (Lieshout & Baddeley 1996). Appliquée au cas des pistes, elle permet de quantifier la fragmentation des paysages. Nous avons calculé l'espace sans routes dans une partie du bassin du Congo, ayant connu une expansion rapide du réseau routier. Nous avons comparé l'évolution temporelle de l'espace sans routes dans les concessions forestières certifiées et non certifiées à l'intérieur et à l'extérieur des zones déclarées IFL pour l'année 2000.

Nous avons ainsi montré que la fragmentation des forêts dans les paysages définis comme « intacts » en 2000, a augmenté en général, et en particulier dans les concessions certifiées dans le cadre du FSC. Entre 1999 et 2007, l'expansion rapide du réseau routier a conduit à une perte nette de l'espace sans routes dans les IFL. Après 2007, cette trajectoire s'est stabilisée dans la plupart des régions, en raison d'un équilibre entre les pistes nouvellement construites et les pistes abandonnées qui se sont re-végétalisées. Cependant, au sein des concessions situées dans les IFL et qui ont été certifiés par le FSC depuis environ 2007, la diminution de l'espace sans routes s'est poursuivie jusqu'à aujourd'hui, atteignant un niveau comparable à celui observé dans toutes les autres concessions. Seuls les parcs nationaux sont restés sans route. Nous concluons en recommandant que l'aménagement forestier priorise la mise en réserve de la majeure partie de la concession forestière en s'assurant que les anciennes pistes restent inaccessibles. Les politiques de gestion forestière devraient faire de la préservation de vastes zones forestières connectées une priorité absolue en surveillant - et limitant - efficacement l'occupation de l'espace par des routes et pistes accessibles en permanence.

7.7 Recommandations pour l'aménagement des routes et pistes forestières

Le chapitre de conclusion présente, tirées de ces résultats, des propositions pour l'aménagement forestier. Dans les chapitres précédents nous avons identifié les dynamiques spatiales et temporelles à l'oeuvre dans les réseaux routiers liés à l'exploitation forestière en Afrique centrale. La plupart des pistes identifiées à un moment donné dans le passé pourraient ne plus être visibles plus tard, ni sur le terrain ni par télédétection. Cela suggère que la zone influencée négativement par les routes et les pistes est très variable. Ces résultats donnent de nouvelles idées et aident à formuler de nouvelles recommandations pour la gestion des réseaux routiers dans les forêts tropicales. Nous synthétisons ci-dessous nos réflexions sur deux questions importantes : (1) Les pistes anciennement abandonnées devraient-elles être ré-ouvertes au cours des rotations à venir ? (2) Quel rôle peuvent jouer les routes et pistes permanentes dans l'ensemble du réseau et comment leur mise en place dans le paysage peut-elle être optimisée ?

7.7.1 Épargner les forêts en Afrique centrale : Réutiliser les anciennes pistes forestières pour éviter d'en créer de nouvelles

L'aménagement forestière permet l'exploitation récurrente dans la même zone chaque 25-30 ans. Nous montrons que sur les coupes suivantes, les anciennes pistes ne sont pas ré-ouvertes régulièrement (Figure 7.2). Après avoir évalué les bénéfices, les opportunités, les coûts et les risques liés à l'ouverture des pistes, nous concluons que la réouverture de ces pistes mérite une plus grande attention dans l'aménagement, et devrait être priorisée (Kleinschroth *et al.* 2016a). La réouverture pourrait épargner des superficies forestières et limiter les impacts négatifs sur la faune, en particulier liés à la chasse. A plus grande échelle, cela permettrait d'épargner des forêts encore peu ou pas exploitées, grâce à une intensification de l'exploitation dans des zones déjà perturbées.

7.7.2 Comment garder le cœur des forêts tropicales libre de toute route permanente ?

La conception et la gestion des réseaux de routes et pistes forestières nous paraissent un élément clé de la foresterie tropicale durable. Nous avons étudié la persistance des pistes forestières abandonnées et la répartition spatiale des routes et pistes forestières actives dans les paysages forestiers. Nous en avons conclu que les routes et pistes dans les forêts peuvent différer fondamentalement dans leurs impacts écologiques, selon la manière dont elles sont construites et entretenues. La majorité du réseau routier pour l'exploitation forestière se compose de pistes d'extraction temporaires qui relient les arbres exploités avec la piste d'accès. Les pistes sont généralement construites de manière ramifiée, chaque branche menant à un certain nombre de « culs-de-sac ». Après chaque récolte, ces pistes sont abandonnées et fermées à la circulation motorisée. Nous avons montré que, malgré le succès limité de la fermeture des pistes sur le court terme, la révégétalisation rendait l'accès par des véhicules motorisés très difficile sur le plus long terme. Ceci suggère que la plupart des pistes,non permanentes ne constituent pas des

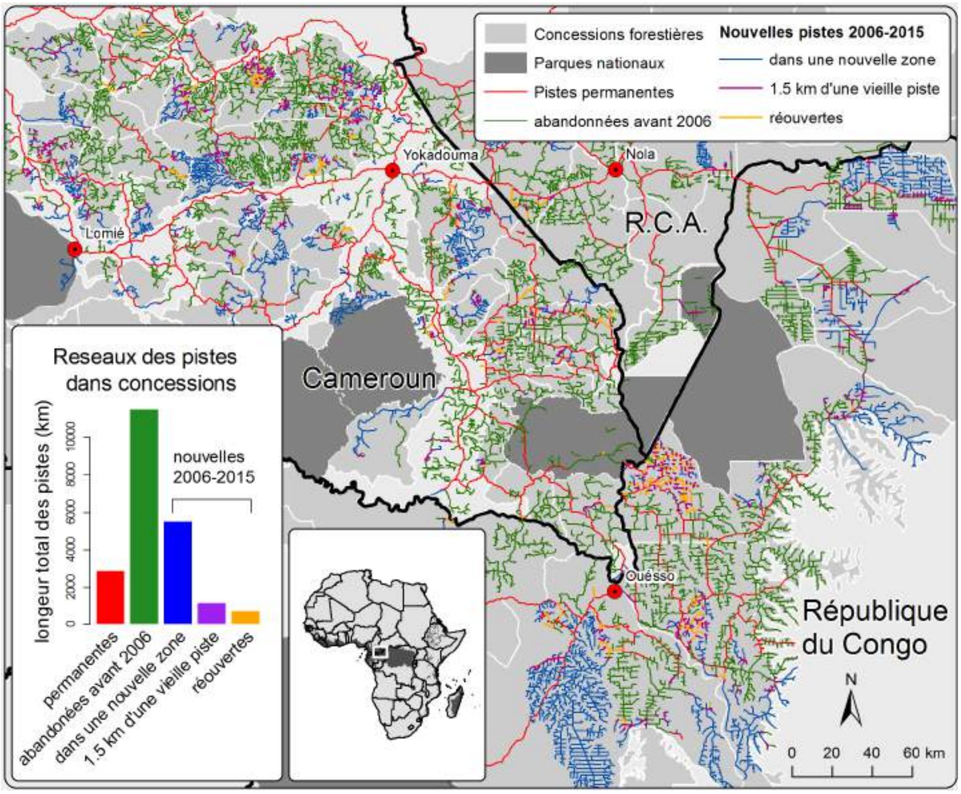

FIGURE 7.2 – Réseau routier dans une zone forestière de 108 000 km^2 en Afrique centrale. Nous avons digitalisé les routes et les pistes en utilisant 222 images LANDSAT prises entre 1985 et 2015 et déterminé 1) pendant combien de temps ils restaient ouverts et 2) comment ils se revégétalisaient en raison de l'abandon et/ ou de la fermeture des pistes d'exploitation (Kleinschroth et al. 2015). Nous avons regroupé les pistes en fonction de leur ouverture dans trois intervalles de temps : (1) 1985-2001, (2) 2002-2005, ou (3) 2006-2015. Nous avons ensuite déterminé quelles routes ou pistes étaient permanentes [ouvertes lors des intervalles (1), (2), ET (3), ou ouvertes en (2) ET (3), lignes rouges], ont été abandonnées avant 2006 [(1) ET / OU (2), vert], ont été ré-ouvertes au cours de la période 2006-2015 [(1) ET (3), orange], ou ont été nouvellement construites pendant la période 2006-2015 [uniquement (3)]. Nous avons ensuite identifié quelles pistes nouvellement construites étaient situées dans des zones "intactes" (bleu) ou précédemment exploitées (violet) – les pistes situées dans une zone tampon de 1,5 km de chaque côté de toutes les anciennes pistes, non permanentes (basé sur la distance de débardage maximal). Le contrôle au sol a été réalisé lors d'un parcours d'environ 2000 km, pendant la réalisation des inventaires de végétation sur les pistes abandonnées. Les concessions forestières (www.wri.org) et les parcs nationaux (www.protectedplanet.net) sont montrés en gris. Petites fenêtres : longueur totale des routes et pistes pour chaque catégorie et emplacement de la zone d'étude en Afrique (http ://maps.tnc.org). RCA = République centrafricaine.

menaces pour l'écosystème forestier sur le long terme. Cependant, les routes et pistes permanentes sont utilisées et entretenues pour avoir un accès à la forêt. Bien que l'accès soit souvent limité par une barrière gardée, on peut se demander dans quelle mesure ce contrôle est efficace, surtout dans les zones les plus éloignées, étant données la mauvaise gouvernance et la pression des populations voisines. Les routes et pistes accessibles en permanence peuvent agir comme des catalyseurs de la déforestation et de la dégradation des forêts. Ils peuvent former des noyaux à partir duquel un nouveau réseau de voies d'accès peut se développer. Nous considérons donc qu'il est crucial pour la gestion durable des forêts de contrôler le positionnement et la durée d'accessibilité des routes et pistes, avec une attention particulière à porter aux routes et pistes accessibles simultanément.

Nous suggérons l'apport de modifications à la stratégie générale de conception des pistes d'exploitation dans les forêts tropicales, afin de maximiser l'étendue des espaces sans routes. L'exploitation forestière devrait chercher à maximiser la taille de l'espace sans routes à tout moment pour inclure le concept de paysages forestiers intacts (IFL) dans l'exploitation à faible impact (RIL). L'aménagement des réseaux de pistes dans les forêts tropicales devrait inclure la planification active d'éléments transitoires dans le paysage en les rendant complètement inaccessibles jusqu'à leur réouverture. En parallèle, les routes et pistes d'accès permanentes devraient être localisées à la périphérie de la forêt.

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